

Karatsuba Multiplication for Integers

Jakob Schulz, Emin Karayel

May 14, 2024

Abstract

We give a verified implementation of the Karatsuba Multiplication on Integers [1] as well as verified runtime bounds. Integers are represented as LSBF (least significant bit first) boolean lists, on which the algorithm by Karatsuba [1] is implemented. The running time of $O(n^{\log_2 3})$ is verified using the Time Monad defined in [2].

Contents

1	Preliminaries	3
2	Auxiliary Sum Lemmas	9
2.1	<i>semiring-1</i> Sums	11
2.1.1	Power Sums	13
2.2	<i>nat</i> Sums	16
3	Sums in Monoids	18
3.1	Kronecker delta	25
3.2	Power sums	26
3.2.1	Algebraic operations	28
3.3	<i>monoid-sum-list</i> in the context <i>residues</i>	30
4	The <i>estimation</i> tactic	30
5	Some Automation for <i>Root-Balanced-Tree.Time-Monad</i>	31
6	Running Time Formalization for some functions available in <i>Main</i>	32
6.1	Functions on <i>bool</i>	32
6.1.1	Not	32
6.1.2	disj / conj	32
6.1.3	equal	32
6.2	Functions involving pairs	33
6.2.1	<i>fst</i> / <i>snd</i>	33

6.3	Functions on <i>nat</i>	33
6.3.1	(+)	33
6.3.2	(*)	33
6.3.3	(\wedge)	34
6.3.4	(-)	35
6.3.5	(<) / (\leq)	35
6.3.6	(=)	36
6.3.7	<i>max</i>	37
6.3.8	(<i>div</i>) / (<i>mod</i>)	37
6.3.9	(<i>dvd</i>)	40
6.3.10	<i>even</i> / <i>odd</i>	40
6.4	List functions	40
6.4.1	<i>take</i>	40
6.4.2	<i>drop</i>	41
6.4.3	(@)	41
6.4.4	<i>fold</i>	41
6.4.5	<i>rev</i>	42
6.4.6	<i>replicate</i>	42
6.4.7	<i>length</i>	42
6.4.8	<i>List.null</i>	42
6.4.9	<i>butlast</i>	43
6.4.10	<i>map</i>	43
6.4.11	<i>foldl</i>	44
6.4.12	<i>concat</i>	44
6.4.13	(!)	45
6.4.14	<i>zip</i>	45
6.4.15	<i>map2</i>	46
6.4.16	<i>upt</i>	46
6.5	Syntactic sugar	47
7	Representations	49
7.1	Abstract Representations	49
7.2	Abstract Representations 2	51
8	Representing <i>nat</i> in LSBF	54
8.1	Type definition	55
8.2	Conversions	55
8.3	Truncating and filling	59
8.4	Right-shifts	66
8.5	Subdividing lists	67
8.5.1	Splitting a list in two blocks	67
8.5.2	Splitting a list in multiple blocks	67
8.6	The <i>bitsize</i> function	71
8.6.1	The <i>next-power-of-2</i> function	73

8.7	Addition	75
8.7.1	Increment operation	75
8.7.2	Addition with a carry bit	77
8.7.3	Addition	83
8.8	Comparison and subtraction	84
8.8.1	Comparison	84
8.8.2	Subtraction	86
8.9	(Grid) Multiplication	89
8.10	Syntax bundles	90
9	Running time of <i>Nat-LSBF</i>	95
9.1	Truncating and filling	96
9.2	Right-shifts	97
9.3	Subdividing lists	97
9.3.1	Splitting a list in two blocks	97
9.3.2	Splitting a list in multiple blocks	98
9.4	The <i>bitsize</i> function	99
9.4.1	The <i>is-power-of-2</i> function	99
9.5	Addition	101
9.6	Comparison and subtraction	103
9.7	(Grid) Multiplication	106
9.8	Syntax bundles	107
10	Representing <i>int</i> in LSBF	108
10.1	Type definition	108
10.2	Conversions	108
10.3	Addition	109
10.4	Grid Multiplication	110
11	Karatsuba Multiplication	110
12	Running Time of Karatsuba Multiplication	120
13	Code Generation	132

1 Preliminaries

Some general preliminaries.

theory *Karatsuba-Preliminaries*

imports *Main Expander-Graphs.Extra-Congruence-Method HOL-Number-Theory.Residues*
begin

lemma *prop-iffI*:

assumes $Q \implies P$ R

assumes $\neg Q \implies P$ S

shows P (if Q then R else S)
 using *assms* by *argo*

lemma *let-prop-cong*:
 assumes $T = T'$
 assumes $P (f T) (f' T')$
 shows $P (\text{let } x = T \text{ in } f x) (\text{let } x = T' \text{ in } f' x)$
 using *assms* by *simp*

lemma *set-subseteqD*:
 assumes $\text{set } xs \subseteq A$
 shows $\bigwedge i. i < \text{length } xs \implies xs ! i \in A$
 using *assms* by *fastforce*

lemma *set-subseteqI*:
 assumes $\bigwedge i. i < \text{length } xs \implies xs ! i \in A$
 shows $\text{set } xs \subseteq A$
 using *assms*
 by (*metis in-set-conv-nth subsetI*)

lemma *Nat-max-le-sum*: $\max (a :: \text{nat}) b \leq a + b$
 by *simp*

lemma *upt-add-eq-append'*:
 assumes $a \leq b$ $b \leq c$
 shows $[a..<c] = [a..<b] @ [b..<c]$
 using *assms* *upt-add-eq-append[of a b c - b]* by *auto*

lemma *map-add-const-upt*: $\text{map } (\lambda j. j + c) [a..<b] = [a + c..<b + c]$
proof (*cases a < b*)
 case *True*
 then have $\text{map } (\lambda j. j + c) [a..<b] = \text{map } (\lambda j. j + c) (\text{map } (\lambda j. j + a) [0..<b-a])$
 using *map-add-upt[of a b - a]* by *simp*
 also have $\dots = \text{map } (\lambda j. j + (a + c)) [0..<b-a]$
 by *simp*
 also have $\dots = [a+c..<b+c]$
 using *map-add-upt[of a + c b - a]* *True* by *simp*
 finally show *?thesis* .
 next
 case *False*
 then show *?thesis* by *simp*
qed

lemma *filter-even-upt-even*: $\text{filter even } [0..<2*n] = \text{map } ((* 2) [0..<n]$
 by (*induction n*) *simp-all*

lemma *filter-even-upt-odd*: $\text{filter even } [0..<2*n + 1] = \text{map } ((* 2) [0..<n + 1]$
 by (*simp add: filter-even-upt-even*)

lemma *filter-odd-upt-even*: $\text{filter odd } [0..<2*n] = \text{map } (\lambda i. 2*i + 1) [0..<n]$

by (induction n) simp-all
lemma filter-odd-upt-odd: filter odd [0.. $2*n + 1$] = map ($\lambda i. 2*i + 1$) [0.. n]
 by (simp add: filter-odd-upt-even)

lemma length-filter-even: length (filter even [0.. n]) = (if even n then n div 2 else n div 2 + 1)
 by (induction n) simp-all
lemma length-filter-odd: length (filter odd [0.. n]) = n div 2
 by (induction n) simp-all

lemma filter-even-nth:
 assumes $i < \text{length (filter even [0.. n])}$
 shows filter even [0.. n] ! $i = 2 * i$
proof (cases even n)
 case True
 then obtain n' where $n = 2 * n'$ by blast
 then show ?thesis using filter-even-upt-even[of n'] assms by auto
next
 case False
 then obtain n' where $n = 2 * n' + 1$ using oddE by blast
 show ?thesis
 using assms
 apply (simp only: $\langle n = 2 * n' + 1 \rangle$ filter-even-upt-odd length-map nth-map)
 apply (intro arg-cong[where $f = (*) 2$])
 by (metis add-0 diff-zero length-upt nth-upt)
qed

lemma filter-odd-nth:
 assumes $i < \text{length (filter odd [0.. n])}$
 shows filter odd [0.. n] ! $i = 2 * i + 1$
proof (cases even n)
 case True
 then obtain n' where $n = 2 * n'$ by blast
 then show ?thesis using filter-odd-upt-even assms by auto
next
 case False
 then obtain n' where $n = 2 * n' + 1$ using oddE by blast
 then show ?thesis
 using assms
 by (simp only: filter-odd-upt-odd length-map)
 (simp add: $\langle n = 2 * n' + 1 \rangle$ length-filter-odd)
qed

fun sublist where
 sublist 0 n xs = take n xs
 | sublist (Suc m) (Suc n) (a # xs) = sublist m n xs
 | sublist (Suc m) 0 xs = []
 | sublist (Suc m) (Suc n) [] = []

lemma *length-sublist[simp]*: $\text{length} (\text{sublist } m \ n \ xs) = \text{card} (\{m..<n\} \cap \{0..<\text{length } xs\})$

by (*induction m n xs rule: sublist.induct*) *simp-all*

lemma *length-sublist'*:

assumes $m \leq n$

assumes $n \leq \text{length } xs$

shows $\text{length} (\text{sublist } m \ n \ xs) = n - m$

using *assms* **by** *simp*

lemma *nth-sublist*:

assumes $m \leq n$

assumes $n \leq \text{length } xs$

assumes $i < n - m$

shows $\text{sublist } m \ n \ xs \ ! \ i = xs \ ! \ (m + i)$

using *assms*

by (*induction m n xs arbitrary: i rule: sublist.induct*) *simp-all*

lemma *filter-map-map2*:

assumes $\text{length } b = m$

assumes $\text{length } c = m$

shows $[f \ (b!i) \ (c!i). \ i \leftarrow [0..<m]] = \text{map2 } f \ b \ c$

using *assms* **by** (*intro nth-equalityI*) *simp-all*

fun *map3* **where**

$\text{map3 } f \ (x \ \# \ xs) \ (y \ \# \ ys) \ (z \ \# \ zs) = f \ x \ y \ z \ \# \ \text{map3 } f \ xs \ ys \ zs$

| $\text{map3 } f \ - \ - \ - = []$

lemma *map3-as-map*: $\text{map3 } f \ xs \ ys \ zs = \text{map} (\lambda((x, y), z). f \ x \ y \ z) (\text{zip} (\text{zip } xs \ ys) \ zs)$

by (*induction f xs ys zs rule: map3.induct; simp*)

lemma *filter-map-map3*:

assumes $\text{length } b = m$

assumes $\text{length } c = m$

shows $[f \ (b!i) \ (c!i) \ i. \ i \leftarrow [0..<m]] = \text{map3 } f \ b \ c \ [0..<m]$

using *assms*

apply (*intro nth-equalityI*)

unfolding *map3-as-map* **by** *simp-all*

fun *map4* **where**

$\text{map4 } f \ (x \ \# \ xs) \ (y \ \# \ ys) \ (z \ \# \ zs) \ (w \ \# \ ws) = f \ x \ y \ z \ w \ \# \ \text{map4 } f \ xs \ ys \ zs \ ws$

| $\text{map4 } f \ - \ - \ - \ - = []$

lemma *map4-as-map*: $\text{map4 } f \ xs \ ys \ zs \ ws = \text{map} (\lambda(((x,y),z),w). f \ x \ y \ z \ w) (\text{zip} (\text{zip } xs \ ys) \ zs) \ ws)$

by (*induction f xs ys zs ws rule: map4.induct; simp*)

lemma *nth-map2*:

assumes $i < \text{length } xs$
assumes $i < \text{length } ys$
shows $\text{map2 } f \text{ } xs \text{ } ys ! i = f (xs ! i) (ys ! i)$
using *assms* **by** *simp*

lemma *nth-map3*:
assumes $i < \text{length } xs$
assumes $i < \text{length } ys$
assumes $i < \text{length } zs$
shows $\text{map3 } f \text{ } xs \text{ } ys \text{ } zs ! i = f (xs ! i) (ys ! i) (zs ! i)$
using *assms* **unfolding** *map3-as-map* **by** *simp*

lemma *nth-map4*:
assumes $i < \text{length } xs$
assumes $i < \text{length } ys$
assumes $i < \text{length } zs$
assumes $i < \text{length } ws$
shows $\text{map4 } f \text{ } xs \text{ } ys \text{ } zs \text{ } ws ! i = f (xs ! i) (ys ! i) (zs ! i) (ws ! i)$
using *assms* **unfolding** *map4-as-map* **by** *simp*

lemma *nth-map4'*:
assumes $i < l$
assumes $\text{length } xs = l$
assumes $\text{length } ys = l$
assumes $\text{length } zs = l$
assumes $\text{length } ws = l$
shows $\text{map4 } f \text{ } xs \text{ } ys \text{ } zs \text{ } ws ! i = f (xs ! i) (ys ! i) (zs ! i) (ws ! i)$
using *assms* **unfolding** *map4-as-map* **by** *simp*

lemma *map2-of-map-r*: $\text{map2 } f \text{ } xs (\text{map } g \text{ } ys) = \text{map2 } (\lambda x y. f x (g y)) \text{ } xs \text{ } ys$
by (*intro nth-equalityI*) *simp-all*

lemma *map2-of-map-l*: $\text{map2 } f (\text{map } g \text{ } xs) \text{ } ys = \text{map2 } (\lambda x y. f (g x) y) \text{ } xs \text{ } ys$
by (*intro nth-equalityI*) *simp-all*

lemma *map2-of-map2-r*: $\text{map2 } f \text{ } xs (\text{map2 } g \text{ } ys \text{ } zs) = \text{map3 } (\lambda x y z. f x (g y z)) \text{ } xs \text{ } ys \text{ } zs$
unfolding *map3-as-map* **by** (*intro nth-equalityI*) *simp-all*

lemma *map-of-map3*: $\text{map } f (\text{map3 } g \text{ } xs \text{ } ys \text{ } zs) = \text{map3 } (\lambda x y z. f (g x y z)) \text{ } xs \text{ } ys \text{ } zs$
unfolding *map3-as-map* **by** (*intro nth-equalityI*) *simp-all*

lemma *cyclic-index-lemma*:
fixes $n :: \text{nat}$
assumes $\sigma < n \ \varrho < n \ i < n$
shows $(\sigma + \varrho) \bmod n = i \iff \varrho = (n + i - \sigma) \bmod n$
proof
assume $(\sigma + \varrho) \bmod n = i$
then have $(\text{int } \sigma + \text{int } \varrho) \bmod (\text{int } n) = \text{int } i$
using *zmod-int* **by** *fastforce*
also have $\dots = (\text{int } n + \text{int } i) \bmod \text{int } n$
using $\langle i < n \rangle$ **by** *auto*
finally have $(\text{int } \sigma + \text{int } \varrho - \text{int } \sigma) \bmod (\text{int } n) = (\text{int } n + \text{int } i - \text{int } \sigma) \bmod \text{int } n$

```

    using mod-diff-cong by blast
  then have (int ρ) mod (int n) = (int n + int i - int σ) mod (int n)
    by simp
  also have ... = (int (n + i - σ)) mod (int n)
    using assms by (simp add: int-ops(6))
  finally show ρ = (n + i - σ) mod n
    using zmod-int assms by (metis mod-less of-nat-eq-iff)
next
  assume ρ = (n + i - σ) mod n
  then have (σ + ρ) mod n = (σ + (n + i - σ)) mod n
    by presburger
  also have ... = (n + i) mod n
    using assms by simp
  also have ... = i
    using assms by simp
  finally show (σ + ρ) mod n = i .
qed

```

lemma (in *residues*) *residues-minus-eq*: $x \ominus_R y = (x - y) \bmod m$
proof –

```

  have  $x \ominus_R y = x \oplus_R (\ominus_R y)$ 
    using a-minus-def by fast
  also have  $\ominus_R y = (-y) \bmod m$ 
    using res-neg-eq[of y] .
  also have  $x \oplus_R ((-y) \bmod m) = (x + ((-y) \bmod m)) \bmod m$ 
    by (simp add: R-m-def residue-ring-def)
  also have ... =  $(x - y) \bmod m$ 
    by (simp add: mod-add-right-eq)
  finally show ?thesis .
qed

```

lemma *residue-ring-carrier-eq*: $\{0..(n::int) - 1\} = \{0..<n\}$
 by *auto*

context *ring*
begin

```

fun nat-embedding :: nat ⇒ 'a where
  nat-embedding 0 = 0
  | nat-embedding (Suc n) = nat-embedding n ⊕ 1
fun int-embedding :: int ⇒ 'a where
  int-embedding n = (if n ≥ 0 then nat-embedding (nat n) else ⊖ nat-embedding (nat
  (-n)))

```

lemma *nat-embedding-closed[simp]*: $\text{nat-embedding } x \in \text{carrier } R$
 by (induction x)(simp-all)

lemma *int-embedding-closed[simp]*: $\text{int-embedding } x \in \text{carrier } R$
 by *simp*

lemma *nat-embedding-a-hom*: $\text{nat-embedding } (x + y) = \text{nat-embedding } x \oplus \text{nat-embedding } y$
apply (*induction x arbitrary: y*)
using *a-comm a-assoc* **by** *simp-all*
lemma *nat-embedding-m-hom*: $\text{nat-embedding } (x * y) = \text{nat-embedding } x \otimes \text{nat-embedding } y$
apply (*induction x arbitrary: y*)
by (*simp-all add: nat-embedding-a-hom l-distr a-comm*)
lemma *nat-embedding-exp-hom*: $\text{nat-embedding } (x \hat{\ } y) = \text{nat-embedding } x [\hat{\ }] y$
apply (*induction y*)
by (*simp-all add: nat-embedding-m-hom group-commutes-pow*)
lemma *int-embedding-neg-hom*: $\text{int-embedding } (- x) = \ominus \text{int-embedding } x$
by *simp*

end

lemma *int-exp-hom*: $\text{int } x \hat{\ } i = \text{int } (x \hat{\ } i)$
by *simp*

end

2 Auxiliary Sum Lemmas

theory *Karatsuba-Sum-Lemmas*

imports *Karatsuba-Preliminaries Expander-Graphs.Extra-Congruence-Method*

begin

lemma *sum-list-eq*: $(\bigwedge x. x \in \text{set } xs \implies f x = g x) \implies \text{sum-list } (\text{map } f xs) = \text{sum-list } (\text{map } g xs)$
by (*rule arg-cong[OF list.map-cong0]*)

lemma *sum-list-split-0*: $(\sum i \leftarrow [0..< \text{Suc } n]. f i) = f 0 + (\sum i \leftarrow [1..< \text{Suc } n]. f i)$

using *upt-eq-Cons-conv*

proof –

have $[0..< \text{Suc } n] = 0 \# [1..< \text{Suc } n]$ **using** *upt-eq-Cons-conv* **by** *auto*

then show *?thesis* **by** *simp*

qed

lemma *sum-list-index-trafo*: $(\sum i \leftarrow xs. f (g i)) = (\sum i \leftarrow \text{map } g xs. f i)$

by (*induction xs*) *simp-all*

lemma *sum-list-index-shift*: $(\sum i \leftarrow [a..< b]. f (i + c)) = (\sum i \leftarrow [a+c..< b+c]. f i)$

proof –

have $(\sum i \leftarrow [a..< b]. f (i + c)) = (\sum i \leftarrow (\text{map } (\lambda j. j + c) [a..< b]). f i)$

by (*intro sum-list-index-trafo*)

also have $\text{map } (\lambda j. j + c) [a..< b] = [a+c..< b+c]$

using *map-add-const-upt* **by** *simp*

finally show *?thesis* .

qed

lemma *list-sum-index-shift*: $n = j - k \implies (\sum i \leftarrow [k+1..<j+1]. f i) = (\sum i \leftarrow [k..<j]. f (i + 1))$
using *sum-list-index-trafo*[**where** $g = \lambda l. l + 1$ **and** $xs = [k..<j]$ **and** $f = f$, *symmetric*]
using *map-Suc-upt* **by** *simp*

lemma *list-sum-index-shift'*: $(\sum i \leftarrow [0..<m]. a (i + c)) = (\sum i \leftarrow [c..<m+c]. a i)$
by (*induction m arbitrary: a c*) *auto*

lemma *list-sum-index-concat*: $(\sum i \leftarrow [0..<m]. a i) + (\sum i \leftarrow [m..<m+c]. a i) = (\sum i \leftarrow [0..<m+c]. a i)$

proof –

have $(\sum i \leftarrow [0..<m+c]. a i) = (\sum i \leftarrow [0..<m] @ [m..<m+c]. a i)$
using *upt-add-eq-append*[*of 0 m c*] **by** *simp*
then show *?thesis* **using** *sum-list-append* **by** *simp*

qed

lemma *sum-list-linear*:

assumes $\bigwedge a b. f (a + b) = f a + f b$
assumes $f 0 = 0$
shows $f (\sum i \leftarrow xs. g i) = (\sum i \leftarrow xs. f (g i))$
using *assms*
by (*induction xs*) *simp-all*

lemma *sum-list-int*:

shows $\text{int} (\sum i \leftarrow xs. g i) = (\sum i \leftarrow xs. \text{int} (g i))$
by (*intro sum-list-linear int-ops(5) int-ops(1)*)

lemma *sum-list-split-Suc*:

assumes $n = \text{Suc } n'$
shows $(\sum i \leftarrow [0..<n]. f i) = (\sum i \leftarrow [0..<n']. f i) + f n'$
using *assms* **by** *simp*

lemma *sum-list-estimation-leq*:

assumes $\bigwedge i. i \in \text{set } xs \implies f i \leq B$
shows $(\sum i \leftarrow xs. f i) \leq \text{length } xs * B$
using *assms* **by** (*induction xs*)(*simp, fastforce*)

lemma *sum-list-estimation-le*:

assumes $\bigwedge i. i \in \text{set } xs \implies f i < B$
assumes $xs \neq []$
shows $(\sum i \leftarrow xs. f i) < \text{length } xs * B$

proof –

from $\langle xs \neq [] \rangle$ **have** $\text{length } xs > 0$ **by** *simp*
from $\langle xs \neq [] \rangle$ **obtain** x **where** $x \in \text{set } xs$ **by** *fastforce*
then have $B > 0$ **using** *assms(1)* **by** *fastforce*
then obtain B' **where** $B = \text{Suc } B'$ **using** *not0-implies-Suc* **by** *blast*
with *assms(1)* **have** $\bigwedge i. i \in \text{set } xs \implies f i \leq B'$ **by** *fastforce*

with *sum-list-estimation-leq* **have** $(\sum i \leftarrow xs. f i) \leq \text{length } xs * B'$ **by** *blast*
also have $\dots < \text{length } xs * B$ **using** $\langle B = \text{Suc } B' \rangle \langle \text{length } xs > 0 \rangle$ **by** *simp*
finally show *?thesis* .
qed

2.1 *semiring-1* Sums

lemma (**in** *semiring-1*) *of-bool-mult*: $\text{of-bool } x * a = (\text{if } x \text{ then } a \text{ else } 0)$
by *simp*

lemma (**in** *semiring-1-cancel*) *of-bool-disj*: $\text{of-bool } (x \vee y) = \text{of-bool } x + \text{of-bool } y$
 $- \text{of-bool } x * \text{of-bool } y$
by *simp*

lemma (**in** *semiring-1*) *of-bool-disj-excl*: $\neg (x \wedge y) \implies \text{of-bool } (x \vee y) = \text{of-bool } x + \text{of-bool } y$
by *simp*

lemma (**in** *semiring-1*) *of-bool-var-swap*:

$(\sum i \leftarrow xs. \text{of-bool } (i = j) * f i) = (\sum i \leftarrow xs. \text{of-bool } (i = j) * f j)$
by (*induction xs*) *simp-all*

lemma $(\sum i \leftarrow xs. \text{of-bool } (i = j) * f i) = \text{count-list } xs \ j * f j$
by (*induction xs*) *simp-all*

lemma (**in** *semiring-1*) *of-bool-distinct*:

$\text{distinct } xs \implies (\sum i \leftarrow xs. \text{of-bool } (i = j) * f i j) = \text{of-bool } (j \in \text{set } xs) * f j j$
by (*induction xs*) *auto*

lemma (**in** *semiring-1*) *of-bool-distinct-in*:

$\text{distinct } xs \implies j \in \text{set } xs \implies (\sum i \leftarrow xs. \text{of-bool } (i = j) * f i j) = f j j$
using *of-bool-distinct[of xs j f]* *of-bool-mult* **by** *simp*

lemma (**in** *linordered-semiring-1*) *of-bool-sum-leq-1*:

assumes *distinct xs*

assumes $\bigwedge i j. i \in \text{set } xs \implies j \in \text{set } xs \implies P i \implies P j \implies i = j$

shows $(\sum l \leftarrow xs. \text{of-bool } (P l)) \leq 1$

using *assms*

proof (*induction xs*)

case *Nil*

then show *?case* **by** *simp*

next

case (*Cons a xs*)

consider $P a \mid \neg P a$ **by** *blast*

then show *?case*

proof *cases*

case *1*

then have $r: (\sum l \leftarrow a \# xs. \text{of-bool } (P l)) = 1 + (\sum l \leftarrow xs. \text{of-bool } (P l))$

by *simp*

have $\text{of-bool } (P l) = 0$ **if** $l \in \text{set } xs$ **for** l

proof $-$

from that have $a \neq l$ **using** *Cons* **by** *auto*

then have $\neg P l$ **using** *Cons* $\langle l \in \text{set } xs \rangle$ *1* **by** *force*

```

    then show  $of\text{-}bool (P l) = 0$  by simp
  qed
  then have  $(\sum l \leftarrow xs. of\text{-}bool (P l)) = (\sum l \leftarrow xs. 0)$ 
    using list.map-cong0[of xs] by metis
  then show ?thesis using r by simp
next
  case 2
  then have  $(\sum l \leftarrow a \# xs. of\text{-}bool (P l)) = (\sum l \leftarrow xs. of\text{-}bool (P l))$ 
    by simp
  then show ?thesis using Cons by simp
qed
qed
instantiation nat :: linordered-semiring-1
begin
  instance ..
end

lemma (in semiring-1) sum-list-mult-sum-list:  $(\sum i \leftarrow xs. f i) * (\sum j \leftarrow ys. g j)$ 
=  $(\sum i \leftarrow xs. \sum j \leftarrow ys. f i * g j)$ 
  by (simp add: sum-list-const-mult sum-list-mult-const)

lemma (in semiring-1) semiring-1-sum-list-eq:
 $(\bigwedge i. i \in set\ xs \implies f i = g i) \implies (\sum i \leftarrow xs. f i) = (\sum i \leftarrow xs. g i)$ 
  using arg-cong[OF list.map-cong0] by blast

lemma (in semiring-1) sum-swap:
 $(\sum i \leftarrow xs. (\sum j \leftarrow ys. f i j)) = (\sum j \leftarrow ys. (\sum i \leftarrow xs. f i j))$ 
proof (induction xs)
  case (Cons a xs)
  have  $(\sum i \leftarrow (a \# xs). (\sum j \leftarrow ys. f i j)) = (\sum j \leftarrow ys. f a j) + (\sum i \leftarrow xs. (\sum j \leftarrow ys. f i j))$ 
    by simp
  also have  $\dots = (\sum j \leftarrow ys. f a j) + (\sum j \leftarrow ys. (\sum i \leftarrow xs. f i j))$ 
    using Cons by simp
  also have  $\dots = (\sum j \leftarrow ys. f a j + (\sum i \leftarrow xs. f i j))$ 
    using sum-list-addf[of  $\lambda j. f a j - ys$ ] by simp
  also have  $\dots = (\sum j \leftarrow ys. (\sum i \leftarrow (a \# xs). f i j))$  by simp
  finally show ?case .
qed simp

lemma (in semiring-1) sum-append:
 $(\sum i \leftarrow (xs @ ys). f i) = (\sum i \leftarrow xs. f i) + (\sum i \leftarrow ys. f i)$ 
  by (induction xs) (simp-all add: add.assoc)

lemma (in semiring-1) sum-append':
  assumes  $zs = xs @ ys$ 
  shows  $(\sum i \leftarrow zs. f i) = (\sum i \leftarrow xs. f i) + (\sum i \leftarrow ys. f i)$ 
  using assms sum-append by blast

```

2.1.1 Power Sums

lemma (in *semiring-1*) *sum-list-of-bool-filter*: $(\sum i \leftarrow xs. \text{of-bool } (P \ i) * f \ i) =$
 $(\sum i \leftarrow \text{filter } P \ xs. f \ i)$
by (*induction xs; simp*)

lemma *upt-filter-less*: $\text{filter } (\lambda i. i < c) \ [a..<b] = [a..<\text{min } b \ c]$
by (*induction b; simp*)

lemma *upt-filter-geq*: $\text{filter } (\lambda i. i \geq c) \ [a..<b] = [\text{max } a \ c..<b]$
by (*induction b; simp*)

lemma (in *semiring-1*) *sum-list-of-bool-less*: $(\sum i \leftarrow [a..<b]. \text{of-bool } (i < c) * f \ i)$
 $= (\sum i \leftarrow [a..<\text{min } b \ c]. f \ i)$
unfolding *sum-list-of-bool-filter upt-filter-less* **by** (*rule refl*)

lemma (in *semiring-1*) *sum-list-of-bool-geq*: $(\sum i \leftarrow [a..<b]. \text{of-bool } (i \geq c) * f \ i)$
 $= (\sum i \leftarrow [\text{max } a \ c..<b]. f \ i)$
unfolding *sum-list-of-bool-filter upt-filter-geq* **by** (*rule refl*)

lemma (in *semiring-1*) *sum-list-of-bool-range*: $(\sum i \leftarrow [a..<b]. \text{of-bool } (i \in \text{set } [c..<d]) * f \ i) =$
 $(\sum i \leftarrow [\text{max } a \ c..<\text{min } b \ d]. f \ i)$

proof –

have $(\sum i \leftarrow [a..<b]. \text{of-bool } (i \in \text{set } [c..<d]) * f \ i) =$
 $(\sum i \leftarrow [a..<b]. \text{of-bool } (i \geq c) * (\text{of-bool } (i < d) * f \ i))$
by (*intro semiring-1-sum-list-eq; simp*)

then show *?thesis unfolding sum-list-of-bool-geq sum-list-of-bool-less* .

qed

lemma (in *comm-semiring-1*) *cauchy-product*:
 $(\sum i \leftarrow [0..<n]. f \ i) * (\sum j \leftarrow [0..<m]. g \ j) =$
 $(\sum k \leftarrow [0..<n + m - 1]. \sum l \leftarrow [k + 1 - m..<\text{min } (k + 1) \ n]. f \ l * g \ (k - l))$

proof –

have $(\sum i \leftarrow [0..<n]. f \ i) * (\sum j \leftarrow [0..<m]. g \ j) =$
 $(\sum i \leftarrow [0..<n]. \sum j \leftarrow [0..<m]. f \ i * g \ j)$
unfolding *sum-list-mult-const[symmetric]*
unfolding *sum-list-const-mult[symmetric]*
by (*rule refl*)

also have $\dots = (\sum i \leftarrow [0..<n]. \sum j \leftarrow [0..<m]. \sum k \leftarrow [0..<n + m - 1].$
 $\text{of-bool } (k = i + j) * (f \ i * g \ j))$

by (*intro semiring-1-sum-list-eq of-bool-distinct-in[symmetric]; simp*)

also have $\dots = (\sum k \leftarrow [0..<n + m - 1]. \sum i \leftarrow [0..<n]. \sum j \leftarrow [0..<m].$
 $\text{of-bool } (k = i + j) * (f \ i * g \ j))$

unfolding *sum-swap[where xs = [0..<m] and ys = [0..<n + m - 1]]*

unfolding *sum-swap[where xs = [0..<n] and ys = [0..<n + m - 1]]*

by (*rule refl*)

also have $\dots = (\sum k \leftarrow [0..<n + m - 1]. \sum i \leftarrow [0..<n]. \sum j \leftarrow [0..<m].$
 $\text{of-bool } (k \geq i \wedge j = k - i) * (f \ i * g \ j))$

by (*intro semiring-1-sum-list-eq; simp*)
 also have ... = $(\sum k \leftarrow [0..<n + m - 1]. \sum i \leftarrow [0..<n]. \sum j \leftarrow [0..<m].$
of-bool ($j = k - i$) * (*of-bool* ($k \geq i$) * ($f i * g j$)))
 by (*intro semiring-1-sum-list-eq; simp*)
 also have ... = $(\sum k \leftarrow [0..<n + m - 1]. \sum i \leftarrow [0..<n].$ *of-bool* ($k - i \in \text{set}$
 $[0..<m]$) * ((*of-bool* ($k \geq i$) * ($f i * g (k - i)$))))
 by (*intro semiring-1-sum-list-eq of-bool-distinct distinct-upt*)
 also have ... = $(\sum k \leftarrow [0..<n + m - 1]. \sum i \leftarrow [0..<n].$ *of-bool* ($i \geq k + 1 -$
 m) * ((*of-bool* ($k + 1 > i$) * ($f i * g (k - i)$))))
 by (*intro semiring-1-sum-list-eq; auto*)
 also have ... = $(\sum k \leftarrow [0..<n + m - 1]. \sum l \leftarrow [k + 1 - m..<\text{min } (k + 1)$
 $n]. f l * g (k - l))$
 apply (*intro semiring-1-sum-list-eq*)
 unfolding *sum-list-of-bool-geq sum-list-of-bool-less max-0L min.commute*[*of n*]
 by (*rule refl*)
 finally show ?thesis .
 qed

lemma (in *comm-semiring-1*) *power-sum-product*:

assumes $m > 0$

assumes $n \geq m$

shows

$$\begin{aligned}
 & (\sum i \leftarrow [0..<n]. f i * x^{\wedge} i) * (\sum j \leftarrow [0..<m]. g j * x^{\wedge} j) = \\
 & (\sum k \leftarrow [0..<m]. (\sum i \leftarrow [0..<\text{Suc } k]. f i * g (k - i)) * x^{\wedge} k) + \\
 & (\sum k \leftarrow [m..<n]. (\sum i \leftarrow [\text{Suc } k - m..<\text{Suc } k]. f i * g (k - i)) * x^{\wedge} k) + \\
 & (\sum k \leftarrow [n..<n + m - 1]. (\sum i \leftarrow [\text{Suc } k - m..<n]. f i * g (k - i)) * x^{\wedge} k)
 \end{aligned}$$

proof –

have 1: $[0..<n + m - 1] = [0..<m] @ [m..<n] @ [n..<n + m - 1]$

using *upt-add-eq-append'*[*of 0 m n + m - 1*] *upt-add-eq-append'*[*of m n n + m - 1*] *assms* by *simp*

$$\begin{aligned}
 & \text{have } (\sum i \leftarrow [0..<n]. f i * x^{\wedge} i) * (\sum j \leftarrow [0..<m]. g j * x^{\wedge} j) = \\
 & (\sum k \leftarrow [0..<n + m - 1]. \sum l \leftarrow [k + 1 - m..<\text{min } (k + 1) n]. (f l * x^{\wedge} \\
 & l) * (g (k - l) * x^{\wedge} (k - l)))
 \end{aligned}$$

by (*rule cauchy-product*)

also have ... = $(\sum k \leftarrow [0..<n + m - 1]. \sum l \leftarrow [k + 1 - m..<\text{min } (k + 1)$
 $n]. f l * g (k - l) * x^{\wedge} k)$

apply (*intro semiring-1-sum-list-eq*)

using *mult.commute mult.assoc power-add*[*symmetric*]

by *simp*

also have ... = $(\sum k \leftarrow [0..<n + m - 1]. (\sum l \leftarrow [k + 1 - m..<\text{min } (k + 1)$
 $n]. f l * g (k - l)) * x^{\wedge} k)$

by (*intro semiring-1-sum-list-eq sum-list-mult-const*)

also have ... = $(\sum k \leftarrow [0..<m]. (\sum i \leftarrow [k + 1 - m..<\text{min } (k + 1) n]. f i * g (k$
 $- i)) * x^{\wedge} k) +$
 $(\sum k \leftarrow [m..<n]. (\sum i \leftarrow [k + 1 - m..<\text{min } (k + 1) n]. f i * g (k - i)) * x^{\wedge}$
 $k) +$
 $(\sum k \leftarrow [n..<n + m - 1]. (\sum i \leftarrow [k + 1 - m..<\text{min } (k + 1) n]. f i * g (k -$
 $i)) * x^{\wedge} k)$

unfolding 1 sum-append add.assoc by (rule refl)
also have ... = $(\sum k \leftarrow [0..<m]. (\sum i \leftarrow [0..<Suc\ k]. f\ i * g\ (k - i)) * x \wedge k) +$
 $(\sum k \leftarrow [m..<n]. (\sum i \leftarrow [Suc\ k - m..<Suc\ k]. f\ i * g\ (k - i)) * x \wedge k) +$
 $(\sum k \leftarrow [n..<n + m - 1]. (\sum i \leftarrow [Suc\ k - m..<n]. f\ i * g\ (k - i)) * x \wedge k)$
using *assms* **by** (*intro-cong [cong-tag-2 (+)] more: semiring-1-sum-list-eq; simp*)
finally show ?thesis .
qed

lemma (in *comm-semiring-1*) *power-sum-product-same-length*:

assumes $n > 0$

shows $(\sum i \leftarrow [0..<n]. f\ i * x \wedge i) * (\sum j \leftarrow [0..<n]. g\ j * x \wedge j) =$
 $(\sum k \leftarrow [0..<n]. (\sum i \leftarrow [0..<Suc\ k]. f\ i * g\ (k - i)) * x \wedge k) +$
 $(\sum k \leftarrow [n..<2 * n - 1]. (\sum i \leftarrow [Suc\ k - n..<n]. f\ i * g\ (k - i)) * x \wedge k)$
using *power-sum-product[of n n f x g, OF assms order.refl]*
by (*simp add: semiring-numeral-class.mult-2*)

lemma (in *semiring-1*) *sum-index-transformation*:

shows $(\sum i \leftarrow xs. f\ (g\ i)) = (\sum j \leftarrow map\ g\ xs. f\ j)$
by (*induction xs*) *simp-all*

lemma (in *comm-semiring-1*) *power-sum-split*:

fixes $f :: nat \Rightarrow 'a$

fixes $x :: 'a$

fixes $c :: nat$

assumes $j \leq n$

shows $(\sum i \leftarrow [0..<n]. f\ i * x \wedge (i * c)) =$
 $(\sum i \leftarrow [0..<j]. f\ i * x \wedge (i * c)) +$
 $x \wedge (j * c) * (\sum i \leftarrow [0..<n - j]. f\ (j + i) * x \wedge (i * c))$

proof -

have $(\lambda i. i + j) = (+)\ j$ **by** *fastforce*

have $(\sum i \leftarrow [0..<n]. f\ i * x \wedge (i * c)) =$

$(\sum i \leftarrow [0..<j]. f\ i * x \wedge (i * c)) + (\sum i \leftarrow [j..<n]. f\ i * x \wedge (i * c))$

apply (*intro sum-append' upt-add-eq-append'*) **using** $\langle j \leq n \rangle$ **by** *auto*

also have $(\sum i \leftarrow [j..<n]. f\ i * x \wedge (i * c)) =$

$(\sum i \leftarrow map\ ((+)\ j)\ [0..<n - j]. f\ i * x \wedge (i * c))$

apply (*intro-cong [cong-tag-1 sum-list, cong-tag-2 map] more: refl*)

using $\langle j \leq n \rangle$ *map-add-upt[of j n - j]* $\langle \lambda i. i + j = (+)\ j \rangle$ **by** *simp*

also have ... = $(\sum i \leftarrow [0..<n - j]. f\ (j + i) * x \wedge ((j + i) * c))$

by (*intro sum-index-transformation[symmetric]*)

also have ... = $(\sum i \leftarrow [0..<n - j]. x \wedge (j * c) * (f\ (j + i) * x \wedge (i * c)))$

apply (*intro semiring-1-sum-list-eq*)

using *mult.commute mult.assoc* **by** (*simp add: power-add add-mult-distrib*)

also have ... = $x \wedge (j * c) * (\sum i \leftarrow [0..<n - j]. (f\ (j + i) * x \wedge (i * c)))$

by (*intro sum-list-const-mult*)

finally show ?thesis .

qed

2.2 nat Sums

lemma *geo-sum-nat*:

assumes $(q :: nat) > 1$

shows $(q - 1) * (\sum i \leftarrow [0..<n]. q \wedge i) = q \wedge n - 1$

proof (*induction n*)

case (*Suc n*)

have $(q - 1) * (\sum i \leftarrow [0..<Suc\ n]. q \wedge i) = (q - 1) * (q \wedge n + (\sum i \leftarrow [0..<n]. q \wedge i))$

by *simp*

also have $\dots = (q - 1) * q \wedge n + (q - 1) * (\sum i \leftarrow [0..<n]. q \wedge i)$

using *add-mult-distrib mult commute by metis*

also have $\dots = (q - 1) * q \wedge n + (q \wedge n - 1)$

using *Suc.IH by simp*

also have $\dots = q * q \wedge n - 1$ **using** $\langle q > 1 \rangle$ **by** (*simp add: diff-mult-distrib*)

finally show *?case by simp*

qed *simp*

lemma *geo-sum-bound*:

assumes $(q :: nat) > 1$

assumes $\bigwedge i. i < n \implies f\ i < q$

shows $(\sum i \leftarrow [0..<n]. f\ i * q \wedge i) < q \wedge n$

proof –

from *assms* **have** $\bigwedge i. i < n \implies f\ i \leq (q - 1)$ **by** *fastforce*

then have $(\sum i \leftarrow [0..<n]. f\ i * q \wedge i) \leq (\sum i \leftarrow [0..<n]. (q - 1) * q \wedge i)$

apply (*intro sum-list-mono mult-le-mono1*)

using *assms by simp*

also have $\dots = (q - 1) * (\sum i \leftarrow [0..<n]. q \wedge i)$

by (*intro sum-list-const-mult*)

also have $\dots = q \wedge n - 1$

by (*intro geo-sum-nat assms*)

also have $\dots < q \wedge n$ **using** $\langle q > 1 \rangle$ **by** *simp*

finally show *?thesis .*

qed

lemma *power-sum-nat-split-div-mod*:

assumes $x > 1$

assumes $c > 0$

assumes $\bigwedge i. i < n \implies (f\ i :: nat) < x \wedge c$

assumes $j \leq n$

shows $(\sum i \leftarrow [0..<n]. f\ i * x \wedge (i * c)) \text{ div } x \wedge (j * c)$

$= (\sum i \leftarrow [0..<n - j]. f\ (j + i) * x \wedge (i * c))$

$(\sum i \leftarrow [0..<n]. f\ i * x \wedge (i * c)) \text{ mod } x \wedge (j * c)$

$= (\sum i \leftarrow [0..<j]. f\ i * x \wedge (i * c))$

proof –

define *sum* **where** $sum = (\sum i \leftarrow [0..<n]. f\ i * x \wedge (i * c))$

then have $sum = (\sum i \leftarrow [0..<j]. f\ i * x \wedge (i * c)) +$

$x \wedge (j * c) * (\sum i \leftarrow [0..<n - j]. f\ (j + i) * x \wedge (i * c))$

(**is** $sum = ?sum1 + x \wedge (j * c) * ?sum2$)

using *power-sum-split* $\langle j \leq n \rangle$ **by** *blast*


```

have ?sum1 = (∑ i ← [0..<j]. f i * (x ^ c) ^ i)
  apply (intro-cong [cong-tag-2 (*)] more: semiring-1-sum-list-eq refl)
  using power-mult mult.commute by metis
also have ... < (x ^ c) ^ j
  apply (intro geo-sum-bound)
  subgoal using assms one-less-power by blast
  subgoal using assms by simp
done
finally have ?sum1 < x ^ (j * c) by (simp add: power-mult mult.commute)
then show sum mod x ^ (j * c) = ?sum1 sum div (x ^ (j * c)) = ?sum2 using
⟨sum = ?sum1 + x ^ (j * c) * ?sum2⟩
  using assms(1) by fastforce+
qed

```

lemma *power-sum-nat-extract-coefficient*:

```

assumes x > 1
assumes c > 0
assumes ∧i. i < n ⇒ (f i :: nat) < x ^ c
assumes j < n
shows ((∑ i ← [0..<n]. f i * x ^ (i * c)) div x ^ (j * c)) mod x ^ c = f j
proof -
have (∑ i ← [0..<n]. f i * x ^ (i * c)) div x ^ (j * c) =
  (∑ i ← [0..<n - j]. f (j + i) * x ^ (i * c)) (is ?sum = -)
  apply (intro power-sum-nat-split-div-mod(1) assms)
  using assms by simp-all
moreover have ... mod x ^ (1 * c) = (∑ i ← [0..<1]. f (j + i) * x ^ (i * c))
  apply (intro power-sum-nat-split-div-mod(2) assms)
  using assms by simp-all
ultimately show ?sum mod x ^ c = f j by simp
qed

```

lemma *power-sum-nat-eq*:

```

assumes x > 1
assumes c > 0
assumes ∧i. i < n ⇒ (f i :: nat) < x ^ c
assumes ∧i. i < n ⇒ g i < x ^ c
assumes (∑ i ← [0..<n]. f i * x ^ (i * c)) = (∑ i ← [0..<n]. g i * x ^ (i * c))
  (is ?sumf = ?sumg)
shows ∧i. i < n ⇒ f i = g i
proof -
fix i
assume i < n
then have f i = (?sumf div x ^ (i * c)) mod x ^ c
  apply (intro power-sum-nat-extract-coefficient[symmetric] assms) by assumption
also have ... = (?sumg div x ^ (i * c)) mod x ^ c
  using assms by argo
also have ... = g i
  apply (intro power-sum-nat-extract-coefficient assms) using ⟨i < n⟩ by simp-all

```

finally show $f i = g i$.
qed

end

3 Sums in Monoids

theory *Monoid-Sums*

imports *HOL-Algebra.Ring Expander-Graphs.Extra-Congruence-Method Karat-suba-Preliminaries HOL-Library.Multiset HOL-Number-Theory.Residues Karat-suba-Sum-Lemmas*

begin

This section contains a version of *sum-list* for entries in some abelian monoid. Contrary to *sum-list*, which is defined for the type class *comm-monoid-add*, this version is for the locale *abelian-monoid*. After the definition, some simple lemmas about sums are proven for this sum function.

context *abelian-monoid*
begin

fun *monoid-sum-list* :: [$'c \Rightarrow 'a$, $'c \text{ list}$] $\Rightarrow 'a$ where
 $\text{monoid-sum-list } f [] = \mathbf{0}$
 $| \text{monoid-sum-list } f (x \# xs) = f x \oplus \text{monoid-sum-list } f xs$

lemma *monoid-sum-list f xs = foldr* (\oplus) (*map f xs*) $\mathbf{0}$
 by (*induction xs*) *simp-all*

end

The syntactic sugar used for *finsum* is adapted accordingly.

syntax

$\text{-monoid-sum-list} :: \text{index} \Rightarrow \text{idt} \Rightarrow 'c \text{ list} \Rightarrow 'c \Rightarrow 'a$
 $((\exists \oplus \text{--}\leftarrow\text{--} \text{. } \text{-}) [1000, 0, 51, 10] 10)$

translations

$\oplus_{G}^{i \leftarrow xs} . b \Rightarrow \text{CONST } \text{abelian-monoid.monoid-sum-list } G (\lambda i. b) xs$

context *abelian-monoid*
begin

lemma *monoid-sum-list-finsum*:

assumes $\bigwedge i. i \in \text{set } xs \implies f i \in \text{carrier } G$

assumes *distinct xs*

shows $(\oplus i \leftarrow xs. f i) = (\oplus i \in \text{set } xs. f i)$

using *assms*

proof (*induction xs*)

case *Nil*

then show *?case* by *simp*

next

case (*Cons a xs*)
then show ?*case* **using** *finsum-insert*[of set *xs a f*] **by** *simp*
qed

lemma *monoid-sum-list-cong*:
assumes $\bigwedge i. i \in \text{set } xs \implies f i = g i$
shows $(\bigoplus i \leftarrow xs. f i) = (\bigoplus i \leftarrow xs. g i)$
using *assms* **by** (*induction xs*) *simp-all*

lemma *monoid-sum-list-closed*[*simp*]:
assumes $\bigwedge i. i \in \text{set } xs \implies f i \in \text{carrier } G$
shows $(\bigoplus i \leftarrow xs. f i) \in \text{carrier } G$
using *assms* **by** (*induction xs*) *simp-all*

lemma *monoid-sum-list-add-in*:
assumes $\bigwedge i. i \in \text{set } xs \implies f i \in \text{carrier } G$
assumes $\bigwedge i. i \in \text{set } xs \implies g i \in \text{carrier } G$
shows $(\bigoplus i \leftarrow xs. f i) \oplus (\bigoplus i \leftarrow xs. g i) =$
 $(\bigoplus i \leftarrow xs. f i \oplus g i)$

using *assms*
proof (*induction xs*)
case (*Cons a xs*)
have $(\bigoplus i \leftarrow (a \# xs). f i) \oplus (\bigoplus i \leftarrow (a \# xs). g i)$
 $= (f a \oplus (\bigoplus i \leftarrow xs. f i)) \oplus (g a \oplus (\bigoplus i \leftarrow xs. g i))$
by *simp*
also have $\dots = (f a \oplus g a) \oplus ((\bigoplus i \leftarrow xs. f i) \oplus (\bigoplus i \leftarrow xs. g i))$
using *a-comm a-assoc Cons.prem*s **by** *simp*
also have $\dots = (f a \oplus g a) \oplus (\bigoplus i \leftarrow xs. f i \oplus g i)$
using *Cons* **by** *simp*
finally show ?*case* **by** *simp*
qed *simp*

lemma *monoid-sum-list-0*[*simp*]: $(\bigoplus i \leftarrow xs. \mathbf{0}) = \mathbf{0}$
by (*induction xs*) *simp-all*

lemma *monoid-sum-list-swap*:
assumes[*simp*]: $\bigwedge i j. i \in \text{set } xs \implies j \in \text{set } ys \implies f i j \in \text{carrier } G$
shows $(\bigoplus i \leftarrow xs. (\bigoplus j \leftarrow ys. f i j)) =$
 $(\bigoplus j \leftarrow ys. (\bigoplus i \leftarrow xs. f i j))$

using *assms*
proof (*induction xs arbitrary: ys*)
case (*Cons a xs*)
have $(\bigoplus i \leftarrow (a \# xs). (\bigoplus j \leftarrow ys. f i j))$
 $= (\bigoplus j \leftarrow ys. f a j) \oplus (\bigoplus i \leftarrow xs. (\bigoplus j \leftarrow ys. f i j))$
by *simp*
also have $\dots = (\bigoplus j \leftarrow ys. f a j) \oplus (\bigoplus j \leftarrow ys. (\bigoplus i \leftarrow xs. f i j))$
using *Cons* **by** *simp*
also have $\dots = (\bigoplus j \leftarrow ys. f a j \oplus (\bigoplus i \leftarrow xs. f i j))$
using *monoid-sum-list-add-in*[of *ys* $\lambda j. f a j \lambda j. (\bigoplus i \leftarrow xs. f i j)$] *Cons.prem*s

by *simp*
 finally show ?case by *simp*
 qed *simp*

lemma *monoid-sum-list-index-transformation*:
 $(\bigoplus i \leftarrow (\text{map } g \text{ } xs). f i) = (\bigoplus i \leftarrow xs. f (g i))$
 by (*induction xs*) *simp-all*

lemma *monoid-sum-list-index-shift-0*:
 $(\bigoplus i \leftarrow [c..<c+n]. f i) = (\bigoplus i \leftarrow [0..<n]. f (c + i))$
 using *monoid-sum-list-index-transformation*[of $f \lambda i. c + i [0..<n]$]
 by (*simp add: add.commute map-add-upt*)

lemma *monoid-sum-list-index-shift*:
 $(\bigoplus l \leftarrow [a..<b]. f (l+c)) = (\bigoplus l \leftarrow [(a+c)..<(b+c)]. f l)$
 using *monoid-sum-list-index-transformation*[of $f \lambda i. i + c [a..<b]$]
 by (*simp add: map-add-const-upt*)

lemma *monoid-sum-list-app*:
 assumes $\bigwedge i. i \in \text{set } xs \implies f i \in \text{carrier } G$
 assumes $\bigwedge i. i \in \text{set } ys \implies f i \in \text{carrier } G$
 shows $(\bigoplus i \leftarrow xs @ ys. f i) = (\bigoplus i \leftarrow xs. f i) \oplus (\bigoplus i \leftarrow ys. f i)$
 using *assms*
 by (*induction xs*) (*simp-all add: a-assoc*)

lemma *monoid-sum-list-app'*:
 assumes $\bigwedge i. i \in \text{set } xs \implies f i \in \text{carrier } G$
 assumes $\bigwedge i. i \in \text{set } ys \implies f i \in \text{carrier } G$
 assumes $xs @ ys = zs$
 shows $(\bigoplus i \leftarrow zs. f i) = (\bigoplus i \leftarrow xs. f i) \oplus (\bigoplus i \leftarrow ys. f i)$
 using *monoid-sum-list-app* *assms* by *blast*

lemma *monoid-sum-list-extract*:
 assumes $\bigwedge i. i \in \text{set } xs \implies f i \in \text{carrier } G$
 assumes $\bigwedge i. i \in \text{set } ys \implies f i \in \text{carrier } G$
 assumes $f x \in \text{carrier } G$
 shows $(\bigoplus i \leftarrow xs @ x \# ys. f i) = f x \oplus (\bigoplus i \leftarrow (xs @ ys). f i)$
proof –
 have $(\bigoplus i \leftarrow xs @ x \# ys. f i) = (\bigoplus i \leftarrow xs. f i) \oplus f x \oplus (\bigoplus i \leftarrow ys. f i)$
 using *assms monoid-sum-list-app*[of $xs f x \# ys$]
 using *a-assoc* by *auto*
 also have $\dots = f x \oplus ((\bigoplus i \leftarrow xs. f i) \oplus (\bigoplus i \leftarrow ys. f i))$
 using *assms a-assoc a-comm* by *auto*
 finally show ?thesis using *monoid-sum-list-app*[of $xs f ys$] *assms* by *algebra*
 qed

lemma *monoid-sum-list-Suc*:
 assumes $\bigwedge i. i < \text{Suc } r \implies f i \in \text{carrier } G$
 shows $(\bigoplus i \leftarrow [0..<\text{Suc } r]. f i) = (\bigoplus i \leftarrow [0..<r]. f i) \oplus f r$

using *assms monoid-sum-list-app*[of $[0..<r]$ f $[r]$]
by *simp*

lemma *bij-betw-diff-singleton*: $a \in A \implies b \in B \implies \text{bij-betw } f \ A \ B \implies f \ a = b$
 $\implies \text{bij-betw } f \ (A - \{a\}) \ (B - \{b\})$
by (*metis (no-types, lifting) DiffE Diff-Diff-Int Diff-cancel Diff-empty Int-insert-right-if1 Un-Diff-Int notIn-Un-bij-betw3 singleton-iff*)

lemma $a \in A \implies \text{bij-betw } f \ A \ B \implies \text{bij-betw } f \ (A - \{a\}) \ (B - \{f \ a\})$
using *bij-betw-diff-singleton*[of $a \ A \ f \ a \ B \ f$]
by (*simp add: bij-betwE*)

lemma *monoid-sum-list-multiset-eq*:
assumes $\text{mset } xs = \text{mset } ys$
assumes $\bigwedge i. i \in \text{set } xs \implies f \ i \in \text{carrier } G$
shows $(\bigoplus i \leftarrow xs. f \ i) = (\bigoplus i \leftarrow ys. f \ i)$
using *assms*
proof (*induction xs arbitrary: ys*)
case *Nil*
then show *?case by simp*
next
case (*Cons a xs*)
then have $a \in \text{set } ys$ **using** *mset-eq-setD* **by** *fastforce*
then obtain $ys1 \ ys2$ **where** $ys = ys1 \ @ \ a \ # \ ys2$ **by** (*meson split-list*)
with *Cons.prem1* **have** $1: \text{mset } xs = \text{mset } (ys1 \ @ \ ys2)$ **by** *simp*
from *Cons.prem1 mset-eq-setD* **have** $\bigwedge i. i \in \text{set } ys \implies f \ i \in \text{carrier } G$ **by** *blast*
then have[*simp*]: $\bigwedge i. i \in \text{set } ys1 \implies f \ i \in \text{carrier } G \ f \ a \in \text{carrier } G \ \bigwedge i. i \in \text{set } ys2 \implies f \ i \in \text{carrier } G$
using $\langle ys = ys1 \ @ \ a \ # \ ys2 \rangle$ **by** *simp-all*
from 1 **have** $(\bigoplus i \leftarrow xs. f \ i) = (\bigoplus i \leftarrow (ys1 \ @ \ ys2). f \ i)$
using *Cons* **by** *simp*
also have $\dots = (\bigoplus i \leftarrow ys1. f \ i) \oplus (\bigoplus i \leftarrow ys2. f \ i)$
by (*intro monoid-sum-list-app*) *simp-all*
also have $f \ a \oplus \dots = (\bigoplus i \leftarrow ys1. f \ i) \oplus (f \ a \oplus (\bigoplus i \leftarrow ys2. f \ i))$
using *a-comm a-assoc monoid-sum-list-closed* **by** *simp*
also have $\dots = (\bigoplus i \leftarrow ys1. f \ i) \oplus (\bigoplus i \leftarrow (a \ # \ ys2). f \ i)$
by *simp*
also have $\dots = (\bigoplus i \leftarrow ys. f \ i)$
unfolding $\langle ys = ys1 \ @ \ a \ # \ ys2 \rangle$
by (*intro monoid-sum-list-app[symmetric]*) *auto*
finally show *?case by simp*

qed

lemma *monoid-sum-list-index-permutation*:
assumes *distinct xs*
assumes $\text{distinct } ys \vee \text{length } xs = \text{length } ys$
assumes $\text{bij-betw } f \ (\text{set } xs) \ (\text{set } ys)$
assumes $\bigwedge i. i \in \text{set } ys \implies g \ i \in \text{carrier } G$
shows $(\bigoplus i \leftarrow ys. g \ i) = (\bigoplus i \leftarrow xs. g \ (f \ i))$
using *assms*

```

proof (induction xs arbitrary: ys)
  case Nil
  then have ys = [] using bij-betw-same-card by fastforce
  then show ?case by simp
next
  case (Cons a xs)
  then have length ys = length (a # xs) distinct ys
  by (metis bij-betw-same-card distinct-card, metis bij-betw-same-card distinct-card
card-distinct)

  have 0:  $\bigwedge i. i \in \text{set } (a \# xs) \implies g (f i) \in \text{carrier } G$ 
  proof -
    fix i
    assume i  $\in \text{set } (a \# xs)$ 
    then have f i  $\in \text{set } ys$  using Cons.prem3 by (simp add: bij-betw-apply)
    then show g (f i)  $\in \text{carrier } G$  using Cons.prem4 by blast
  qed

  define b where b = f a
  then have b  $\in \text{set } ys$  using Cons(4) bij-betw-apply by fastforce
  then obtain ys1 ys2 where ys = ys1 @ b # ys2 by (meson split-list)
  then have b  $\notin \text{set } ys1$  b  $\notin \text{set } ys2$  using <distinct ys> by simp-all
  have bij-betw f (set xs) (set (ys1 @ ys2))
    using <ys = ys1 @ b # ys2> Cons(4) b-def
    using bij-betw-diff-singleton[of a set (a # xs) f a set ys f]
    using Cons.prem1 <distinct ys> by auto
  moreover have length (ys1 @ ys2) = length xs using <length ys = length (a #
xs)> <ys = ys1 @ b # ys2>
  by simp
  ultimately have 1:  $(\bigoplus i \leftarrow (ys1 @ ys2). g i) = (\bigoplus i \leftarrow xs. g (f i))$  using
Cons.IH[of ys1 @ ys2] Cons.prem4
  using Cons.prem1 0 <ys = ys1 @ b # ys2> by auto

  have  $(\bigoplus i \leftarrow (a \# xs). g (f i)) = g b \oplus (\bigoplus i \leftarrow xs. g (f i))$ 
  using <b = f a> by simp
  also have ... = g b  $\oplus (\bigoplus i \leftarrow (ys1 @ ys2). g i)$  using 1 by simp
  also have ... =  $(\bigoplus i \leftarrow (ys1 @ b # ys2). g i)$ 
  apply (intro monoid-sum-list-extract[symmetric])
  using Cons.prem4 <ys = ys1 @ b # ys2> by simp-all
  finally show  $(\bigoplus i \leftarrow ys. g i) = (\bigoplus i \leftarrow (a \# xs). g (f i))$ 
  using <ys = ys1 @ b # ys2> by simp
qed

lemma monoid-sum-list-split:
  assumes[simp]:  $\bigwedge i. i < b + c \implies f i \in \text{carrier } G$ 
  shows  $(\bigoplus l \leftarrow [0..<b]. f l) \oplus (\bigoplus l \leftarrow [b..<b + c]. f l) = (\bigoplus l \leftarrow [0..<b + c]. f l)$ 
  using monoid-sum-list-app[of [0..<b] f [b..<b + c], symmetric]
  using upt-add-eq-append[of 0 b c]

```

by *simp*

lemma *monoid-sum-list-splice*:

assumes [*simp*]: $\bigwedge i. i < 2 * n \implies f i \in \text{carrier } G$

shows $(\bigoplus i \leftarrow [0..< 2 * n]. f i) = (\bigoplus i \leftarrow [0..<n]. f (2*i)) \oplus (\bigoplus i \leftarrow [0..<n]. f (2*i+1))$

proof –

let *?es* = *filter even* $[0..< 2 * n]$

let *?os* = *filter odd* $[0..< 2 * n]$

have 1: $(\bigoplus i \leftarrow [0..< 2 * n]. f i) = (\bigoplus i \in \{0..< 2 * n\}. f i)$

using *monoid-sum-list-finsum*[of $[0..< 2 * n]$ *f*] **by** *simp*

let *?E* = $\{i \in \{0..<2*n\}. \text{even } i\}$

let *?O* = $\{i \in \{0..<2*n\}. \text{odd } i\}$

have $?E \cap ?O = \{\}$ **by** *blast*

moreover have $?E \cup ?O = \{0..<2*n\}$ **by** *blast*

ultimately have $(\bigoplus i \in \{0..<2*n\}. f i) = (\bigoplus i \in ?E. f i) \oplus (\bigoplus i \in ?O. f i)$

using *finsum-Un-disjoint*[of *?E ?O f*] *assms* **by** *auto*

moreover have $?E = \text{set } ?es$ $?O = \text{set } ?os$ **by** *simp-all*

ultimately have $(\bigoplus i \in \{0..<2*n\}. f i) = (\bigoplus i \in \text{set } ?es. f i) \oplus (\bigoplus i \in \text{set } ?os. f i)$

by *presburger*

also have $(\bigoplus i \in \text{set } ?es. f i) = (\bigoplus i \leftarrow ?es. f i)$

using *monoid-sum-list-finsum*[of *?es f*] **by** *simp*

also have ... = $(\bigoplus i \leftarrow [0..<n]. f (2*i))$

using *monoid-sum-list-index-transformation*[of *f* $\lambda i. 2 * i$ $[0..<n]$]

using *filter-even-upt-even*

by *algebra*

also have $(\bigoplus i \in \text{set } ?os. f i) = (\bigoplus i \leftarrow ?os. f i)$

using *monoid-sum-list-finsum*[of *?os f*] **by** *simp*

also have ... = $(\bigoplus i \leftarrow [0..<n]. f (2*i + 1))$

using *monoid-sum-list-index-transformation*[of *f* $\lambda i. 2 * i + 1$ $[0..<n]$]

using *filter-odd-upt-even*

by *algebra*

finally show *?thesis* **using** 1 **by** *presburger*

qed

lemma *monoid-sum-list-even-odd-split*:

assumes *even* $(n::\text{nat})$

assumes $\bigwedge i. i < n \implies f i \in \text{carrier } G$

shows $(\bigoplus i \leftarrow [0..<n]. f i) = (\bigoplus i \leftarrow [0..< n \text{ div } 2]. f (2*i)) \oplus (\bigoplus i \leftarrow [0..< n \text{ div } 2]. f (2*i+1))$

using *assms monoid-sum-list-splice* **by** *auto*

end

context *abelian-group*

begin

lemma *monoid-sum-list-minus-in*:

assumes $\bigwedge i. i \in \text{set } xs \implies f i \in \text{carrier } G$
shows $\ominus (\bigoplus i \leftarrow xs. f i) = (\bigoplus i \leftarrow xs. \ominus f i)$
using *assms* **by** (*induction xs*) (*simp-all add: minus-add*)

lemma *monoid-sum-list-diff-in*:

assumes[*simp*]: $\bigwedge i. i \in \text{set } xs \implies f i \in \text{carrier } G$
assumes[*simp*]: $\bigwedge i. i \in \text{set } xs \implies g i \in \text{carrier } G$
shows $(\bigoplus i \leftarrow xs. f i) \ominus (\bigoplus i \leftarrow xs. g i) =$
 $(\bigoplus i \leftarrow xs. f i \ominus g i)$

proof –

have $(\bigoplus i \leftarrow xs. f i) \ominus (\bigoplus i \leftarrow xs. g i) = (\bigoplus i \leftarrow xs. f i) \oplus (\ominus (\bigoplus i \leftarrow xs. g i))$

unfolding *minus-eq* **by** *simp*

also have $\dots = (\bigoplus i \leftarrow xs. f i) \oplus (\bigoplus i \leftarrow xs. \ominus g i)$

using *monoid-sum-list-minus-in*[*of xs g*] **by** *simp*

also have $\dots = (\bigoplus i \leftarrow xs. f i \oplus (\ominus g i))$

using *monoid-sum-list-add-in*[*of xs f*] **by** *simp*

finally show *?thesis* **unfolding** *minus-eq* .

qed

end

context *ring*

begin

lemma *monoid-sum-list-const*:

assumes[*simp*]: $c \in \text{carrier } R$
shows $(\bigoplus i \leftarrow xs. c) = (\text{nat-embedding } (\text{length } xs)) \otimes c$
apply (*induction xs*)
using *a-comm l-distr* **by** *auto*

lemma *monoid-sum-list-in-right*:

assumes $y \in \text{carrier } R$
assumes $\bigwedge i. i \in \text{set } xs \implies f i \in \text{carrier } R$
shows $(\bigoplus i \leftarrow xs. f i \otimes y) = (\bigoplus i \leftarrow xs. f i) \otimes y$
using *assms* **by** (*induction xs*) (*simp-all add: l-distr*)

lemma *monoid-sum-list-in-left*:

assumes $y \in \text{carrier } R$
assumes $\bigwedge i. i \in \text{set } xs \implies f i \in \text{carrier } R$
shows $(\bigoplus i \leftarrow xs. y \otimes f i) = y \otimes (\bigoplus i \leftarrow xs. f i)$
using *assms* **by** (*induction xs*) (*simp-all add: r-distr*)

lemma *monoid-sum-list-prod*:

assumes $\bigwedge i. i \in \text{set } xs \implies f i \in \text{carrier } R$
assumes $\bigwedge i. i \in \text{set } ys \implies g i \in \text{carrier } R$
shows $(\bigoplus i \leftarrow xs. f i) \otimes (\bigoplus j \leftarrow ys. g j) = (\bigoplus i \leftarrow xs. (\bigoplus j \leftarrow ys. f i \otimes g j))$

proof –

have $(\bigoplus i \leftarrow xs. f i) \otimes (\bigoplus j \leftarrow ys. g j) = (\bigoplus i \leftarrow xs. f i \otimes (\bigoplus j \leftarrow ys. g j))$
apply *(intro monoid-sum-list-in-right[symmetric])*
using *assms by simp-all*
also have $\dots = (\bigoplus i \leftarrow xs. (\bigoplus j \leftarrow ys. f i \otimes g j))$
apply *(intro monoid-sum-list-cong monoid-sum-list-in-left[symmetric])*
using *assms by simp-all*
finally show *?thesis .*
qed

3.1 Kronecker delta

definition *delta where*

delta i j = (if i = j then 1 else 0)

lemma *delta-closed[simp]: delta i j ∈ carrier R*
unfolding *delta-def by simp*

lemma *delta-sym: delta i j = delta j i*
unfolding *delta-def by simp*

lemma *delta-refl[simp]: delta i i = 1*
unfolding *delta-def by simp*

lemma *monoid-sum-list-delta[simp]:*

assumes*[simp]:* $\bigwedge i. i < n \implies f i \in \text{carrier } R$

assumes*[simp]:* $j < n$

shows $(\bigoplus i \leftarrow [0..<n]. \text{delta } i j \otimes f i) = f j$

proof –

from *assms have* $0: [0..<n] = [0..<j] @ j \# [Suc j..<n]$

by *(metis le-add1 le-add-same-cancel1 less-imp-add-positive upt-add-eq-append upt-conv-Cons)*

then have $[0..<n] = [0..<j] @ [j] @ [Suc j..<n]$

by *simp*

moreover have $1: \bigwedge i. i \in \text{set } [0..<j] \implies \text{delta } i j \otimes f i \in \text{carrier } R$

using 0 *assms delta-closed m-closed atLeastLessThan-iff*

by *(metis le-add1 less-imp-add-positive linorder-le-less-linear set-upt upt-conv-Nil)*

moreover have $2: \bigwedge i. i \in \text{set } ([j] @ [Suc j..<n]) \implies \text{delta } i j \otimes f i \in \text{carrier } R$

using 0 *assms delta-closed m-closed*

by *auto*

ultimately have $(\bigoplus i \leftarrow [0..<n]. \text{delta } i j \otimes f i) = (\bigoplus i \leftarrow [0..<j]. \text{delta } i j \otimes f i) \oplus (\bigoplus i \leftarrow [j] @ [Suc j..<n]. \text{delta } i j \otimes f i)$

using *monoid-sum-list-app[of [0..<j] λi. delta i j ⊗ f i [j] @ [Suc j..<n]]*

by *presburger*

also have $(\bigoplus i \leftarrow [j] @ [Suc j..<n]. \text{delta } i j \otimes f i) = (\bigoplus i \leftarrow [j]. \text{delta } i j \otimes f i) \oplus (\bigoplus i \leftarrow [Suc j..<n]. \text{delta } i j \otimes f i)$

using 2 *monoid-sum-list-app[of [j] λi. delta i j ⊗ f i [Suc j..<n]]*

by *simp*

also have $(\bigoplus i \leftarrow [0..<j]. \text{delta } i j \otimes f i) = \mathbf{0}$

using *monoid-sum-list-0[of [0..<j]] monoid-sum-list-cong[of [0..<j] λi. 0 λi.*

$\text{delta } i j \otimes f i$
unfolding *delta-def* **using** $\langle j < n \rangle$ **by** *simp*
also have $(\bigoplus i \leftarrow [\text{Suc } j..<n]. \text{delta } i j \otimes f i) = \mathbf{0}$
using *monoid-sum-list-0*[of $[\text{Suc } j..<n]$] *monoid-sum-list-cong*[of $[\text{Suc } j..<n]$]
 $\lambda i. \mathbf{0} \lambda i. \text{delta } i j \otimes f i$
unfolding *delta-def* **by** *simp*
also have $(\bigoplus i \leftarrow [j]. \text{delta } i j \otimes f i) = f j$ **by** *simp*
finally show *?thesis* **by** *simp*
qed

lemma *monoid-sum-list-only-delta*[*simp*]:
 $j < n \implies (\bigoplus i \leftarrow [0..<n]. \text{delta } i j) = \mathbf{1}$
using *monoid-sum-list-delta*[of $n \lambda i. \mathbf{1} j$] **by** *simp*

3.2 Power sums

lemma *geo-monoid-list-sum*:
assumes[*simp*]: $x \in \text{carrier } R$
shows $(\mathbf{1} \ominus x) \otimes (\bigoplus l \leftarrow [0..<r]. x [\uparrow] l) = (\mathbf{1} \ominus x [\uparrow] r)$
using *assms*
proof (*induction r*)
case 0
then show *?case* **using** *assms* **by** (*simp, algebra*)
next
case (*Suc r*)
have $(\mathbf{1} \ominus x) \otimes (\bigoplus l \leftarrow [(0::\text{nat})..<\text{Suc } r]. x [\uparrow] l) = (\mathbf{1} \ominus x) \otimes (x [\uparrow] r \oplus (\bigoplus l \leftarrow [0..<r]. x [\uparrow] l))$
using *monoid-sum-list-Suc*[of $r \lambda l. x [\uparrow] l$] *a-comm*
by *simp*

also have $\dots = (\mathbf{1} \ominus x) \otimes x [\uparrow] r \oplus (\mathbf{1} \ominus x) \otimes (\bigoplus l \leftarrow [0..<r]. x [\uparrow] l)$
using *r-distr* **by** *auto*
also have $\dots = x [\uparrow] r \oplus x [\uparrow] (\text{Suc } r) \oplus (\mathbf{1} \ominus x) \otimes (\bigoplus l \leftarrow [0..<r]. x [\uparrow] l)$
apply (*intro arg-cong2*[**where** $f = (\oplus)$] *refl*)
unfolding *minus-eq*
 $l\text{-distr}[OF \text{ one-closed } a\text{-inv-closed}[OF \langle x \in \text{carrier } R \rangle] \text{ nat-pow-closed}[OF \langle x \in \text{carrier } R \rangle]]$
using $\langle x \in \text{carrier } R \rangle$
using *l-minus nat-pow-Suc2* **by** *force*
also have $\dots = x [\uparrow] r \oplus x [\uparrow] (\text{Suc } r) \oplus (\mathbf{1} \ominus x [\uparrow] r)$
using *Suc* **by** *presburger*
also have $\dots = \mathbf{1} \ominus x [\uparrow] (\text{Suc } r)$
using *one-closed minus-add assms nat-pow-closed*[of x] **by** *algebra*
finally show *?case* .
qed

rewrite $?x \in \text{carrier } R \implies (?x [\uparrow] ?n) [\uparrow] ?m = ?x [\uparrow] (?n * ?m)$ and $?a * ?b = ?b * ?a$ inside power sum

lemma *monoid-pow-sum-nat-pow-pow*:

assumes $x \in \text{carrier } R$
shows $(\bigoplus i \leftarrow xs. f i \otimes x [\ulcorner] ((g i :: \text{nat}) * h i)) = (\bigoplus i \leftarrow xs. f i \otimes (x [\ulcorner] h i) [\ulcorner] g i)$
apply (*intro-cong* [*cong-tag-2* (\otimes)] *more: monoid-sum-list-cong refl*)
using *nat-pow-pow*[*OF assms*] **by** (*simp add: mult commute*)

end

context *cring*
begin

Split a power sum at some term

lemma *monoid-pow-sum-list-split*:

assumes $l + k = n$
assumes $\bigwedge i. i < n \implies f i \in \text{carrier } R$
assumes $x \in \text{carrier } R$
shows $(\bigoplus i \leftarrow [0..<n]. f i \otimes x [\ulcorner] i) =$
 $(\bigoplus i \leftarrow [0..<l]. f i \otimes x [\ulcorner] i) \oplus$
 $x [\ulcorner] l \otimes (\bigoplus i \leftarrow [0..<k]. f (l + i) \otimes x [\ulcorner] i)$
proof –
have $(\bigoplus i \leftarrow [0..<n]. f i \otimes x [\ulcorner] i) =$
 $(\bigoplus i \leftarrow [0..<l]. f i \otimes x [\ulcorner] i) \oplus$
 $(\bigoplus i \leftarrow [l..<n]. f i \otimes x [\ulcorner] i)$
apply (*intro monoid-sum-list-app'* *m-closed nat-pow-closed upt-add-eq-append'*[*symmetric*])
using *assms* **by** *simp-all*
also have $(\bigoplus i \leftarrow [l..<n]. f i \otimes x [\ulcorner] i) =$
 $(\bigoplus i \leftarrow [0..<k]. f (l + i) \otimes x [\ulcorner] (l + i))$
using *monoid-sum-list-index-shift-0*[*of - l n - l*] $\langle l + k = n \rangle$
by *fastforce*
also have $\dots = (\bigoplus i \leftarrow [0..<k]. x [\ulcorner] l \otimes (f (l + i) \otimes x [\ulcorner] i))$
apply (*intro monoid-sum-list-cong*)
using *assms m-comm m-assoc nat-pow-mult*[*symmetric, OF* $\langle x \in \text{carrier } R \rangle$]
by *simp*
also have $\dots = x [\ulcorner] l \otimes (\bigoplus i \leftarrow [0..<k]. f (l + i) \otimes x [\ulcorner] i)$
apply (*intro monoid-sum-list-in-left* *m-closed nat-pow-closed*)
using *assms* **by** *simp-all*
finally show *?thesis* .

qed

split power sum at term, more general

lemma *monoid-pow-sum-split*:

assumes $l + k = n$
assumes $\bigwedge i. i < n \implies f i \in \text{carrier } R$
assumes $x \in \text{carrier } R$
shows $(\bigoplus i \leftarrow [0..<n]. f i \otimes x [\ulcorner] (i * c)) =$
 $(\bigoplus i \leftarrow [0..<l]. f i \otimes x [\ulcorner] (i * c)) \oplus$
 $x [\ulcorner] (l * c) \otimes (\bigoplus i \leftarrow [0..<k]. f (l + i) \otimes x [\ulcorner] (i * c))$
proof –
have $(\bigoplus i \leftarrow [0..<n]. f i \otimes x [\ulcorner] (i * c)) = (\bigoplus i \leftarrow [0..<n]. f i \otimes (x [\ulcorner] c) [\ulcorner]$

i)
 by (*intro monoid-pow-sum-nat-pow-pow* $\langle x \in \text{carrier } R \rangle$)
 also have ... = $(\bigoplus i \leftarrow [0..<l]. f\ i \otimes (x\ [\uparrow]\ c)\ [\uparrow]\ i) \oplus$
 $(x\ [\uparrow]\ c)\ [\uparrow]\ l \otimes (\bigoplus i \leftarrow [0..<k]. f\ (l + i) \otimes (x\ [\uparrow]\ c)\ [\uparrow]\ i)$
 by (*intro monoid-pow-sum-list-split assms nat-pow-closed*) *argo*
 also have ... = $(\bigoplus i \leftarrow [0..<l]. f\ i \otimes x\ [\uparrow]\ (i * c)) \oplus$
 $x\ [\uparrow]\ (c * l) \otimes (\bigoplus i \leftarrow [0..<k]. f\ (l + i) \otimes x\ [\uparrow]\ (i * c))$
 by (*intro-cong [cong-tag-2* (\oplus), *cong-tag-2* (\otimes)] *more: monoid-pow-sum-nat-pow-pow[symmetric]*
nat-pow-pow $\langle x \in \text{carrier } R \rangle$)
 also have ... = $(\bigoplus i \leftarrow [0..<l]. f\ i \otimes x\ [\uparrow]\ (i * c)) \oplus$
 $x\ [\uparrow]\ (l * c) \otimes (\bigoplus i \leftarrow [0..<k]. f\ (l + i) \otimes x\ [\uparrow]\ (i * c))$
 by (*intro-cong [cong-tag-2* (\oplus), *cong-tag-2* (\otimes), *cong-tag-2* ($[\uparrow]$)] *more: refl*
mult commute)
 finally show *?thesis* .
 qed

3.2.1 Algebraic operations

addition

lemma *monoid-pow-sum-add*:

assumes $\bigwedge i. i \in \text{set } xs \implies f\ i \in \text{carrier } R$

assumes $\bigwedge i. i \in \text{set } xs \implies g\ i \in \text{carrier } R$

assumes $x \in \text{carrier } R$

shows $(\bigoplus i \leftarrow xs. f\ i \otimes x\ [\uparrow]\ (i::\text{nat})) \oplus (\bigoplus i \leftarrow xs. g\ i \otimes x\ [\uparrow]\ i) = (\bigoplus i \leftarrow xs. (f\ i \oplus g\ i) \otimes x\ [\uparrow]\ i)$

proof –

have $(\bigoplus i \leftarrow xs. f\ i \otimes x\ [\uparrow]\ i) \oplus (\bigoplus i \leftarrow xs. g\ i \otimes x\ [\uparrow]\ i) =$

$(\bigoplus i \leftarrow xs. (f\ i \otimes x\ [\uparrow]\ i) \oplus (g\ i \otimes x\ [\uparrow]\ i))$

apply (*intro monoid-sum-list-add-in m-closed nat-pow-closed assms*) by *assumption+*

also have ... = $(\bigoplus i \leftarrow xs. (f\ i \oplus g\ i) \otimes x\ [\uparrow]\ i)$

apply (*intro monoid-sum-list-cong l-distr[symmetric]* *nat-pow-closed assms*) by *assumption+*

finally show *?thesis* .

qed

lemma *monoid-pow-sum-add'*:

assumes $\bigwedge i. i \in \text{set } xs \implies f\ i \in \text{carrier } R$

assumes $\bigwedge i. i \in \text{set } xs \implies g\ i \in \text{carrier } R$

assumes $x \in \text{carrier } R$

shows $(\bigoplus i \leftarrow xs. f\ i \otimes x\ [\uparrow]\ ((i::\text{nat}) * c)) \oplus (\bigoplus i \leftarrow xs. g\ i \otimes x\ [\uparrow]\ (i * c)) =$
 $(\bigoplus i \leftarrow xs. (f\ i \oplus g\ i) \otimes x\ [\uparrow]\ (i * c))$

proof –

have $(\bigoplus i \leftarrow xs. f\ i \otimes x\ [\uparrow]\ ((i::\text{nat}) * c)) \oplus (\bigoplus i \leftarrow xs. g\ i \otimes x\ [\uparrow]\ (i * c)) =$

$(\bigoplus i \leftarrow xs. (f\ i \otimes (x\ [\uparrow]\ c)\ [\uparrow]\ i)) \oplus (\bigoplus i \leftarrow xs. (g\ i \otimes (x\ [\uparrow]\ c)\ [\uparrow]\ i))$

by (*intro-cong [cong-tag-2* (\oplus)] *more: monoid-pow-sum-nat-pow-pow* $\langle x \in \text{carrier } R \rangle$)

also have ... = $(\bigoplus i \leftarrow xs. (f\ i \oplus g\ i) \otimes (x\ [\uparrow]\ c)\ [\uparrow]\ i)$

apply (*intro monoid-pow-sum-add nat-pow-closed*) **using** *assms* by *simp-all*

also have ... = $(\bigoplus i \leftarrow xs. (f i \oplus g i) \otimes x [\ulcorner (i * c)])$
 by (intro monoid-pow-sum-nat-pow-pow[symmetric] ‹x ∈ carrier R›)

finally show ?thesis .

qed

unary minus

lemma monoid-pow-sum-minus:

assumes $\bigwedge i. i \in \text{set } xs \implies f i \in \text{carrier } R$

assumes $x \in \text{carrier } R$

shows $\ominus (\bigoplus i \leftarrow xs. f i \otimes x [\ulcorner (i :: \text{nat})]) = (\bigoplus i \leftarrow xs. (\ominus f i) \otimes x [\ulcorner i])$

proof –

have $\ominus (\bigoplus i \leftarrow xs. f i \otimes x [\ulcorner (i :: \text{nat})]) = (\bigoplus i \leftarrow xs. \ominus (f i \otimes x [\ulcorner (i :: \text{nat})]))$

apply (intro monoid-sum-list-minus-in m-closed nat-pow-closed assms) by assumption

also have ... = $(\bigoplus i \leftarrow xs. (\ominus f i) \otimes x [\ulcorner i])$

apply (intro monoid-sum-list-cong l-minus[symmetric] nat-pow-closed assms)

by assumption

finally show ?thesis .

qed

minus

lemma monoid-pow-sum-diff:

assumes $\bigwedge i. i \in \text{set } xs \implies f i \in \text{carrier } R$

assumes $\bigwedge i. i \in \text{set } xs \implies g i \in \text{carrier } R$

assumes $x \in \text{carrier } R$

shows $(\bigoplus i \leftarrow xs. f i \otimes x [\ulcorner (i :: \text{nat})]) \ominus (\bigoplus i \leftarrow xs. g i \otimes x [\ulcorner (i :: \text{nat})]) =$
 $(\bigoplus i \leftarrow xs. (f i \ominus g i) \otimes x [\ulcorner i])$

using assms

by (simp add: minus-eq monoid-pow-sum-add[symmetric] monoid-pow-sum-minus)

lemma monoid-pow-sum-diff':

assumes $\bigwedge i. i \in \text{set } xs \implies f i \in \text{carrier } R$

assumes $\bigwedge i. i \in \text{set } xs \implies g i \in \text{carrier } R$

assumes $x \in \text{carrier } R$

shows $(\bigoplus i \leftarrow xs. f i \otimes x [\ulcorner ((i :: \text{nat}) * c)]) \ominus (\bigoplus i \leftarrow xs. g i \otimes x [\ulcorner (i * c)]) =$
 $(\bigoplus i \leftarrow xs. (f i \ominus g i) \otimes x [\ulcorner (i * c)])$

proof –

have $(\bigoplus i \leftarrow xs. f i \otimes x [\ulcorner ((i :: \text{nat}) * c)]) \ominus (\bigoplus i \leftarrow xs. g i \otimes x [\ulcorner (i * c)]) =$

$(\bigoplus i \leftarrow xs. f i \otimes (x [\ulcorner c] [\ulcorner i]) \ominus (\bigoplus i \leftarrow xs. g i \otimes (x [\ulcorner c] [\ulcorner i]))$

by (intro-cong [cong-tag-2] (λ i j. i ⊖ j)) more: monoid-pow-sum-nat-pow-pow ‹x ∈ carrier R›)

also have ... = $(\bigoplus i \leftarrow xs. (f i \ominus g i) \otimes (x [\ulcorner c] [\ulcorner i]))$

apply (intro monoid-pow-sum-diff nat-pow-closed) using assms by simp-all

also have ... = $(\bigoplus i \leftarrow xs. (f i \ominus g i) \otimes x [\ulcorner (i * c)])$

by (intro monoid-pow-sum-nat-pow-pow[symmetric] ‹x ∈ carrier R›)

finally show ?thesis .

qed

end

3.3 monoid-sum-list in the context residues

context *residues*

begin

lemma *monoid-sum-list-eq-sum-list*:

$(\bigoplus_R i \leftarrow xs. f i) = (\sum i \leftarrow xs. f i) \text{ mod } m$

apply (*induction xs*)

subgoal by (*simp add: zero-cong*)

subgoal for *a xs* **by** (*simp add: mod-add-right-eq res-add-eq*)

done

lemma *monoid-sum-list-mod-in*:

$(\bigoplus_R i \leftarrow xs. f i) = (\bigoplus_R i \leftarrow xs. (f i) \text{ mod } m)$

by (*induction xs*) (*simp-all add: mod-add-left-eq res-add-eq*)

lemma *monoid-sum-list-eq-sum-list'*:

$(\bigoplus_R i \leftarrow xs. f i \text{ mod } m) = (\sum i \leftarrow xs. f i) \text{ mod } m$

using *monoid-sum-list-eq-sum-list monoid-sum-list-mod-in* **by** *metis*

end

end

4 The estimation tactic

theory *Estimation-Method*

imports *Main HOL-Eisbach.Eisbach-Tools*

begin

A few useful lemmas for working with inequalities.

lemma *if-prop-cong*:

assumes $C = C'$

assumes $C \implies P A A'$

assumes $\neg C \implies P B B'$

shows P (*if C then A else B*) (*if C' then A' else B'*)

using *assms* **by** *simp*

lemma *if-leqI*:

assumes $C \implies A \leq t$

assumes $\neg C \implies B \leq t$

shows (*if C then A else B*) $\leq t$

using *assms* **by** *simp*

lemma *if-le-max*:

(*if C then (t1 :: 'a :: linorder) else t2*) $\leq \max t1 t2$

by *simp*

Prove some inequality by showing a chain of inequalities via an intermediate

term.

```
method itrans for step :: 'a :: order =
  (match conclusion in  $s \leq t$  for  $s t :: 'a \Rightarrow \langle \text{rule } \text{order.trans}[of\ s\ step\ t] \rangle$ )
```

A collection of monotonicity intro rules that will be automatically used by *estimation*.

```
lemmas mono-intros =
  order.refl add-mono diff-mono mult-le-mono max.mono min.mono power-increasing
  power-mono
  iffD2[OF Suc-le-mono] if-prop-cong[where  $P = (\leq)$ ] Nat.le0 one-le-numeral
```

Try to apply a given estimation rule *estimate* in a forward-manner.

```
method estimation uses estimate =
  (match estimate in  $\bigwedge a. f\ a \leq h\ a$  (multi) for  $f\ h \Rightarrow \langle$ 
    match conclusion in  $g\ f \leq t$  for  $g$  and  $t :: \text{nat} \Rightarrow$ 
     $\langle \text{rule } \text{order.trans}[of\ g\ f\ g\ h\ t], \text{intro } \text{mono-intros refl } \text{estimate} \rangle \rangle$ 
```

```
|  $x \leq y$  for  $x\ y \Rightarrow \langle$ 
  match conclusion in  $g\ x \leq t$  for  $g$  and  $t :: \text{nat} \Rightarrow$ 
   $\langle \text{rule } \text{order.trans}[of\ g\ x\ g\ y\ t], \text{intro } \text{mono-intros refl } \text{estimate} \rangle \rangle$ 
```

```
end
theory Time-Monad-Extended
  imports Root-Balanced-Tree.Time-Monad
begin
```

5 Some Automation for *Root-Balanced-Tree.Time-Monad*

A bit of automation for statements involving the *time* component.

```
lemma time-bind-tm:  $\text{time } (s \ggg f) = \text{time } s + \text{time } (f\ (\text{val } s))$ 
  unfolding bind-tm-def
  by (simp split: tm.splits)
```

```
lemma time-tick:  $\text{time } (\text{tick } s) = 1$ 
  by (simp add: tick-def)
```

```
lemmas tm-time-simps[simp] = time-bind-tm time-return time-tick if-distrib[of
time]
```

```
lemma bind-tm-cong[fundef-cong]:
  assumes  $f1 = f2$ 
  assumes  $g1\ (\text{val } f1) = g2\ (\text{val } f2)$ 
  shows  $f1 \ggg g1 = f2 \ggg g2$ 
  using assms unfolding bind-tm-def
  by (auto split: tm.splits)
```

Introduce *val-simp* as named theorem. The idea is to collect simplification rules for the *Time-Monad.val* component that can be unfolded on their own.

```

named-theorems val-simp
declare val-simps[val-simp]

end
theory Main-TM
  imports Main Time-Monad-Extended Estimation-Method
begin

```

6 Running Time Formalization for some functions available in *Main*

6.1 Functions on *bool*

6.1.1 Not

```

fun Not-tm :: bool  $\Rightarrow$  bool tm where
  Not-tm True = 1 return False
  | Not-tm False = 1 return True

```

```

lemma val-Not-tm[simp, val-simp]: val (Not-tm x) = Not x
  by (cases x; simp)

```

```

lemma time-Not-tm[simp]: time (Not-tm x) = 1
  by (cases x; simp)

```

6.1.2 disj / conj

```

definition disj-tm where disj-tm x y = 1 return (x  $\vee$  y)
definition conj-tm where conj-tm x y = 1 return (x  $\wedge$  y)

```

```

lemma val-disj-tm[simp, val-simp]: val (disj-tm x y) = (x  $\vee$  y)
  by (simp add: disj-tm-def)

```

```

lemma time-disj-tm[simp]: time (disj-tm x y) = 1
  by (simp add: disj-tm-def)

```

```

lemma val-conj-tm[simp, val-simp]: val (conj-tm x y) = (x  $\wedge$  y)
  by (simp add: conj-tm-def)

```

```

lemma time-conj-tm[simp]: time (conj-tm x y) = 1
  by (simp add: conj-tm-def)

```

6.1.3 equal

```

fun equal-bool-tm :: bool  $\Rightarrow$  bool  $\Rightarrow$  bool tm where
  equal-bool-tm True p = 1 return p
  | equal-bool-tm False p = 1 Not-tm p

```

```

lemma val-equal-bool-tm[simp, val-simp]: val (equal-bool-tm x y) = (x = y)
  by (cases x; simp)

```

```

lemma time-equal-bool-tm-le: time (equal-bool-tm x y)  $\leq$  2

```


by (cases x; simp)

6.2 Functions involving pairs

6.2.1 fst / snd

fun *fst-tm* :: 'a × 'b ⇒ 'a tm **where**

fst-tm (x, y) = 1 return x

fun *snd-tm* :: 'a × 'b ⇒ 'b tm **where**

snd-tm (x, y) = 1 return y

lemma *val-fst-tm*[simp, val-simp]: val (*fst-tm* p) = *fst* p

by (subst prod.collapse[symmetric], unfold *fst-tm.simps*, simp)

lemma *time-fst-tm*[simp]: time (*fst-tm* p) = 1

by (subst prod.collapse[symmetric], unfold *fst-tm.simps*, simp)

lemma *val-snd-tm*[simp, val-simp]: val (*snd-tm* p) = *snd* p

by (subst prod.collapse[symmetric], unfold *snd-tm.simps*, simp)

lemma *time-snd-tm*[simp]: time (*snd-tm* p) = 1

by (subst prod.collapse[symmetric], unfold *snd-tm.simps*, simp)

6.3 Functions on nat

6.3.1 (+)

fun *plus-nat-tm* :: nat ⇒ nat ⇒ nat tm **where**

plus-nat-tm (Suc m) n = 1 *plus-nat-tm* m (Suc n)

| *plus-nat-tm* 0 n = 1 return n

lemma *val-plus-nat-tm*[simp, val-simp]: val (*plus-nat-tm* m n) = m + n

by (induction m n rule: *plus-nat-tm.induct*) simp-all

lemma *time-plus-nat-tm*[simp]: time (*plus-nat-tm* m n) = m + 1

by (induction m n rule: *plus-nat-tm.induct*) simp-all

6.3.2 (*)

fun *times-nat-tm* :: nat ⇒ nat ⇒ nat tm **where**

times-nat-tm 0 n = 1 return 0

| *times-nat-tm* (Suc m) n = 1 do {

 r ← *times-nat-tm* m n;

plus-nat-tm n r

}

lemma *val-times-nat-tm*[simp]: val (*times-nat-tm* m n) = m * n

by (induction m n rule: *times-nat-tm.induct*) simp-all

lemma *time-times-nat-tm*[simp]: time (*times-nat-tm* m n) = m * (n + 2) + 1

by (induction m n rule: *times-nat-tm.induct*) simp-all

6.3.3 (\wedge)

fun *power-nat-tm* :: *nat* \Rightarrow *nat* \Rightarrow *nat tm* **where**

```
power-nat-tm a 0 = 1 return 1
| power-nat-tm a (Suc n) = 1 do {
  r  $\leftarrow$  power-nat-tm a n;
  times-nat-tm a r
}
```

lemma *val-power-nat-tm*[*simp*, *val-simp*]: *val* (*power-nat-tm* a n) = $a \wedge n$
by (*induction* a n *rule*: *power-nat-tm.induct*) *simp-all*

lemma *time-power-nat-tm-aux0*: *time* (*power-nat-tm* 0 n) = $2 * n + 1$
by (*induction* n) *simp-all*

lemma *time-power-nat-tm-aux1*: *time* (*power-nat-tm* 1 n) = $5 * n + 1$
by (*induction* n) *simp-all*

lemma *time-power-nat-tm-aux2*:

assumes $m \geq 2$

shows *time* (*power-nat-tm* m n) $\leq (2 * n + m \wedge n) * m + 2 * n + 1$

proof (*induction* n)

case 0

then have *time* (*power-nat-tm* m 0) = 1 **by** *simp*

then show ?*case* **by** *simp*

next

case (*Suc* n)

have *time* (*power-nat-tm* m (*Suc* n)) \leq *time* (*power-nat-tm* m n) + ($m \wedge n + 2$) * m + 2

by *simp*

also have ... $\leq (2 * n + m \wedge n) * m + 2 * n + 1 + (m \wedge n + 2) * m + 2$
using *Suc* **by** *simp*

also have ... = $(2 * n + m \wedge n) * m + (m \wedge n + 2) * m + 2 * \text{Suc } n + 1$
by *simp*

also have ... = $(2 * \text{Suc } n + 2 * m \wedge n) * m + 2 * \text{Suc } n + 1$
using *add-mult-distrib* **by** *simp*

also have ... $\leq (2 * \text{Suc } n + m \wedge \text{Suc } n) * m + 2 * \text{Suc } n + 1$
using *assms* **by** *simp*

finally show ?*case* .

qed

lemma *time-power-nat-tm-le*: *time* (*power-nat-tm* m n) $\leq 3 * m \wedge \text{Suc } n + 5 * n + 1$

proof –

consider $m = 0$ | $m = 1$ | $m \geq 2$ **by** *linarith*

then show ?*thesis*

proof *cases*

case 1

then show ?*thesis* **using** *time-power-nat-tm-aux0*[*of* n] **by** *simp*

next

```

    case 2
    then show ?thesis using time-power-nat-tm-aux1[of n] by simp
next
case 3
then have  $2^n \leq m^n$  using power-mono by fast
moreover have  $n < 2^n$  by simp
ultimately have  $n \leq m^n$  by linarith
have time (power-nat-tm m n)  $\leq (2 * m^n + m^n) * m + 2 * n + 1$ 
  apply (estimation estimate: time-power-nat-tm-aux2[OF 3, of n])
  using n-le-m-pow-n by simp
also have ... =  $3 * m^{Suc n} + 2 * n + 1$  by simp
finally show ?thesis by simp
qed
qed

```

```

lemma time-power-nat-tm-2-le: time (power-nat-tm 2 n)  $\leq 12 * 2^n$ 
proof -
  have time (power-nat-tm 2 n)  $\leq 3 * 2^{Suc n} + 5 * n + 1$ 
    by (fact time-power-nat-tm-le)
  also have ...  $\leq 3 * 2^{Suc n} + 5 * 2^n + 2^n$ 
    apply (intro add-mono mult-le-mono order.refl)
    using less-exp[of n] by simp-all
  finally show ?thesis by simp
qed

```

6.3.4 (−)

```

fun minus-nat-tm :: nat  $\Rightarrow$  nat  $\Rightarrow$  nat tm where
  minus-nat-tm m 0 = 1 return m
| minus-nat-tm 0 m = 1 return 0
| minus-nat-tm (Suc m) (Suc n) = 1 minus-nat-tm m n

```

```

lemma val-minus-nat-tm[simp, val-simp]: val (minus-nat-tm m n) = m - n
  by (induction m n rule: minus-nat-tm.induct) simp-all

```

```

lemma time-minus-nat-tm[simp]: time (minus-nat-tm m n) = min m n + 1
  by (induction m n rule: minus-nat-tm.induct) simp-all

```

6.3.5 (<) / (\leq)

```

fun less-eq-nat-tm :: nat  $\Rightarrow$  nat  $\Rightarrow$  bool tm and less-nat-tm :: nat  $\Rightarrow$  nat  $\Rightarrow$  bool
tm where
  less-eq-nat-tm (Suc m) n = 1 less-nat-tm m n
| less-eq-nat-tm 0 n = 1 return True
| less-nat-tm m (Suc n) = 1 less-eq-nat-tm m n
| less-nat-tm m 0 = 1 return False

```

```

lemma val-less-eq-nat-tm[simp, val-simp]: (val (less-eq-nat-tm n m) = (n  $\leq$  m))
and val-less-nat-tm[simp, val-simp]: (val (less-nat-tm m n) = (m < n))
  by (induction m and n rule: less-eq-nat-tm-less-nat-tm.induct) auto

```

lemma *time-less-eq-nat-tm-aux*: $\text{time } (\text{less-eq-nat-tm } (m + k) (n + k)) = 2 * k + \text{time } (\text{less-eq-nat-tm } m n)$
by (*induction k*) *simp-all*

lemma *time-less-nat-tm-aux*: $\text{time } (\text{less-nat-tm } (m + k) (n + k)) = 2 * k + \text{time } (\text{less-nat-tm } m n)$
by (*induction k*) *simp-all*

lemma *time-less-eq-nat-tm*: $\text{time } (\text{less-eq-nat-tm } n m) = 2 * \min n m + 1 + \text{of-bool } (m < n)$
proof (*cases m < n*)

case *True*
then obtain *k* **where** $n = m + \text{Suc } k$ **by** (*metis add-Suc-right less-natE*)
then have $\text{time } (\text{less-eq-nat-tm } n m) = 2 * m + 2$
using *time-less-eq-nat-tm-aux*[*of Suc k m 0*] **by** (*simp add: add.commute*)
then show *?thesis* **using** *True* **by** *simp*

next

case *False*
then obtain *k* **where** $m = n + k$ **using** *nat-le-iff-add*[*of n m*] **by** *auto*
then have $\text{time } (\text{less-eq-nat-tm } n m) = 2 * n + 1$
using *time-less-eq-nat-tm-aux*[*of 0 n k*] **by** (*simp add: add.commute*)
then show *?thesis* **using** *False* **by** *simp*

qed

lemma *time-less-nat-tm*: $\text{time } (\text{less-nat-tm } m n) = 2 * \min m n + 1 + \text{of-bool } (m < n)$

proof (*cases m < n*)

case *True*
then obtain *k* **where** $n = m + \text{Suc } k$ **by** (*metis add-Suc-right less-natE*)
then have $\text{time } (\text{less-nat-tm } m n) = 2 * m + 2$
using *time-less-nat-tm-aux*[*of 0 m Suc k*] **by** (*simp add: add.commute*)
then show *?thesis* **using** *True* **by** *simp*

next

case *False*
then obtain *k* **where** $m = n + k$ **using** *nat-le-iff-add*[*of n m*] **by** *auto*
then have $\text{time } (\text{less-nat-tm } m n) = 2 * n + 1$
using *time-less-nat-tm-aux*[*of k n 0*] **by** (*simp add: add.commute*)
then show *?thesis* **using** *False* **by** *simp*

qed

lemma *time-less-eq-nat-tm-le*: $\text{time } (\text{less-eq-nat-tm } n m) \leq 2 * \min n m + 2$
by (*simp add: time-less-eq-nat-tm*)

lemma *time-less-nat-tm-le*: $\text{time } (\text{less-nat-tm } m n) \leq 2 * \min m n + 2$
by (*simp add: time-less-nat-tm*)

6.3.6 (=)

fun *equal-nat-tm* :: $\text{nat} \Rightarrow \text{nat} \Rightarrow \text{bool } tm$ **where**
equal-nat-tm 0 0 = 1 *return True*
| *equal-nat-tm (Suc x) 0 = 1* *return False*

| *equal-nat-tm* 0 (Suc y) =1 return False
 | *equal-nat-tm* (Suc x) (Suc y) =1 *equal-nat-tm* x y

lemma *val-equal-nat-tm*[*simp*, *val-simp*]: *val* (*equal-nat-tm* x y) = (x = y)
 by (*induction* x y *rule*: *equal-nat-tm.induct*) *simp-all*

lemma *time-equal-nat-tm*: *time* (*equal-nat-tm* x y) = *min* x y + 1
 by (*induction* x y *rule*: *equal-nat-tm.induct*) *simp-all*

6.3.7 max

fun *max-nat-tm* :: *nat* \Rightarrow *nat* \Rightarrow *nat tm* **where**
max-nat-tm x y =1 do {
 b \leftarrow *less-eq-nat-tm* x y;
 if b then return y else return x
}

lemma *val-max-nat-tm*[*simp*, *val-simp*]: *val* (*max-nat-tm* x y) = *max* x y
 by *simp*

lemma *time-max-nat-tm*: *time* (*max-nat-tm* x y) = 2 * *min* x y + 2 + *of-bool* (y < x)
 by (*simp* *add*: *time-less-eq-nat-tm*)

lemma *time-max-nat-tm-le*: *time* (*max-nat-tm* x y) \leq 2 * *min* x y + 3
 unfolding *time-max-nat-tm* by *simp*

6.3.8 (div) / (mod)

fun *divmod-nat-tm* :: *nat* \Rightarrow *nat* \Rightarrow (*nat* \times *nat*) *tm* **where**
divmod-nat-tm m n =1 do {
 n0 \leftarrow *equal-nat-tm* n 0;
 m-lt-n \leftarrow *less-nat-tm* m n;
 b \leftarrow *disj-tm* n0 m-lt-n;
 if b then return (0, m) else do {
 m-minus-n \leftarrow *minus-nat-tm* m n;
 (q, r) \leftarrow *divmod-nat-tm* m-minus-n n;
 return (Suc q, r)
}

declare *divmod-nat-tm.simps*[*simp del*]

lemma *val-divmod-nat-tm*[*simp*, *val-simp*]: *val* (*divmod-nat-tm* m n) = *Euclidean-Rings.divmod-nat* m n

proof (*induction* m n *rule*: *divmod-nat-tm.induct*)
 case (1 m n)
 show ?case
proof (*cases* n = 0 \vee m < n)
 case True

```

then show ?thesis unfolding divmod-nat-tm.simps[of m n] by (simp add: Euclidean-Rings.divmod-nat-if)
next
  case False
  then have val (divmod-nat-tm m n) = (let (q, r) = val (divmod-nat-tm (m - n) n) in (Suc q, r))
    unfolding divmod-nat-tm.simps[of m n]
    by (simp add: Let-def split: prod.splits)
  also have ... = (let (q, r) = Euclidean-Rings.divmod-nat (m - n) n in (Suc q, r))
    using 1 False by simp
  also have ... = Euclidean-Rings.divmod-nat m n
    unfolding Euclidean-Rings.divmod-nat-if[of m n]
    by (simp add: False split: prod.splits)
  finally show ?thesis .
qed
qed

```

```

lemma time-divmod-nat-tm-aux:
  assumes r < n
  assumes n > 0
  shows time (divmod-nat-tm (n * k + r) n) = 5 * k + 3 * n * k + time (divmod-nat-tm r n)
    using assms
proof (induction k)
  case 0
  then show ?case by simp
next
  case (Suc k)
  then show ?case
    unfolding divmod-nat-tm.simps[of n * (Suc k) + r n]
    by (simp add: time-equal-nat-tm time-less-nat-tm split: prod.splits)
qed

```

```

lemma time-divmod-nat-tm-le: time (divmod-nat-tm m n) ≤ 8 * m + 2 * n + 5
proof (cases n = 0 ∨ m < n)
  case True
  have time (divmod-nat-tm m n) = time (equal-nat-tm n 0) + time (less-nat-tm m n) + 2
    unfolding divmod-nat-tm.simps[of m n]
    by (simp add: True)
  also have ... ≤ 2 * min m n + 5
    apply (subst time-equal-nat-tm)
    apply (estimation estimate: time-less-nat-tm-le)
    by simp
  finally show ?thesis by simp
next
  case False

```

```

define  $k\ r$  where  $k = m \text{ div } n\ r = m \text{ mod } n$ 
then have  $k\ r\ n$ :  $m = n * k + r$  by simp
from  $k\ r\ n$ -def have  $r < n$  using False by simp
have  $\text{time}(\text{divmod-nat-tm } m\ n) = 5 * k + 3 * n * k + \text{time}(\text{divmod-nat-tm } r\ n)$ 
apply (subst  $k\ r\ n$ , intro time-divmod-nat-tm-aux, intro  $\langle r < n \rangle$ )
using False by simp
also have  $\text{time}(\text{divmod-nat-tm } r\ n) = \text{time}(\text{equal-nat-tm } n\ 0) + \text{time}(\text{less-nat-tm } r\ n) + 2$ 
unfolding divmod-nat-tm.simps[of  $r\ n$ ]
by (simp add:  $\langle r < n \rangle$ )
also have  $\dots \leq 2 * \min\ r\ n + 5$ 
apply (subst time-equal-nat-tm)
apply (estimation estimate: time-less-nat-tm-le)
by simp
finally have  $\text{time}(\text{divmod-nat-tm } m\ n) \leq 5 * k + 3 * n * k + 2 * n + 5$ 
by simp
also have  $\dots \leq 5 * k + 3 * m + 2 * n + 5$ 
using  $k\ r\ n$ -def by simp
also have  $\dots \leq 8 * m + 2 * n + 5$ 
using  $k\ r\ n$ -def by simp
finally show ?thesis .
qed

```

definition *divide-nat-tm* :: $\text{nat} \Rightarrow \text{nat} \Rightarrow \text{nat tm}$ **where**
divide-nat-tm $m\ n = 1 \text{ divmod-nat-tm } m\ n \gg= \text{fst-tm}$

lemma *val-divide-nat-tm*[*simp*, *val-simp*]: $\text{val}(\text{divide-nat-tm } m\ n) = m \text{ div } n$
by (*simp* *add*: *divide-nat-tm-def* *Euclidean-Rings.divmod-nat-def*)

lemma *time-divide-nat-tm-le*: $\text{time}(\text{divide-nat-tm } m\ n) \leq 8 * m + 2 * n + 7$
using *time-divmod-nat-tm-le*[*of* $m\ n$] **by** (*simp* *add*: *divide-nat-tm-def*)

definition *mod-nat-tm* :: $\text{nat} \Rightarrow \text{nat} \Rightarrow \text{nat tm}$ **where**
mod-nat-tm $m\ n = 1 \text{ divmod-nat-tm } m\ n \gg= \text{snd-tm}$

lemma *val-mod-nat-tm*[*simp*, *val-simp*]: $\text{val}(\text{mod-nat-tm } m\ n) = m \text{ mod } n$
by (*simp* *add*: *mod-nat-tm-def* *Euclidean-Rings.divmod-nat-def*)

lemma *time-mod-nat-tm-le*: $\text{time}(\text{mod-nat-tm } m\ n) \leq 8 * m + 2 * n + 7$
using *time-divmod-nat-tm-le*[*of* $m\ n$] **by** (*simp* *add*: *mod-nat-tm-def*)

definition *dvd-tm* **where** $\text{dvd-tm } a\ b = 1$ **do** {
 $b \text{ mod } a \leftarrow \text{mod-nat-tm } b\ a$;
 $\text{equal-nat-tm } b \text{ mod } a\ 0$
}

6.3.9 (dvd)

lemma *val-dvd-tm*[*simp*, *val-simp*]: *val* (*dvd-tm* *a* *b*) = (*a* *dvd* *b*)
unfolding *dvd-tm-def* *dvd-eq-mod-eq-0* **by** *simp*

lemma *time-dvd-tm-le*: *time* (*dvd-tm* *a* *b*) $\leq 8 * b + 2 * a + 9$
unfolding *dvd-tm-def* *tm-time-simps* *val-mod-nat-tm* *time-equal-nat-tm*
using *time-mod-nat-tm-le*[*of* *b* *a*] **by** *simp*

6.3.10 even / odd

definition *even-tm* **where** *even-tm* *a* = *dvd-tm* 2 *a*

lemma *val-even-tm*[*simp*, *val-simp*]: *val* (*even-tm* *a*) = *even* *a*
unfolding *even-tm-def* **by** *simp*

lemma *time-even-tm-le*: *time* (*even-tm* *a*) $\leq 8 * a + 13$
unfolding *even-tm-def* *tm-time-simps*
using *time-dvd-tm-le*[*of* 2 *a*] **by** *simp*

definition *odd-tm* **where** *odd-tm* *a* = *dvd-tm* 2 *a* \gg *Not-tm*

lemma *val-odd-tm*[*simp*, *val-simp*]: *val* (*odd-tm* *a*) = *odd* *a*
unfolding *odd-tm-def* **by** *simp*

lemma *time-odd-tm-le*: *time* (*odd-tm* *a*) $\leq 8 * a + 14$
unfolding *odd-tm-def* *tm-time-simps*
using *time-dvd-tm-le*[*of* 2 *a*] **by** *simp*

6.4 List functions

6.4.1 take

fun *take-tm* :: *nat* \Rightarrow '*a* *list* \Rightarrow '*a* *list* *tm* **where**
take-tm *n* [] = 1 *return* []
| *take-tm* *n* (*x* # *xs*) = 1 (*case* *n* *of* 0 \Rightarrow *return* [] | *Suc* *m* \Rightarrow
 do {
 r \leftarrow *take-tm* *m* *xs*;
 return (*x* # *r*)
 }
})

lemma *val-take-tm*[*simp*, *val-simp*]: *val* (*take-tm* *n* *xs*) = *take* *n* *xs*
by (*induction* *n* *xs* *rule*: *take-tm.induct*) (*simp-all* *split*: *nat.splits*)

lemma *time-take-tm*: *time* (*take-tm* *n* *xs*) = *min* *n* (*length* *xs*) + 1
by (*induction* *n* *xs* *rule*: *take-tm.induct*) (*simp-all* *split*: *nat.splits*)

lemma *time-take-tm-le*: *time* (*take-tm* *n* *xs*) $\leq n + 1$
by (*simp* *add*: *time-take-tm*)

6.4.2 drop

```
fun drop-tm :: nat ⇒ 'a list ⇒ 'a list tm where
drop-tm n [] =1 return []
| drop-tm n (x # xs) =1 (case n of 0 ⇒ return (x # xs) | Suc m ⇒
  do {
    r ← drop-tm m xs;
    return r
  })
```

lemma val-drop-tm[*simp*, *val-simp*]: val (drop-tm n xs) = drop n xs
by (induction n xs rule: drop-tm.induct) (simp-all split: nat.splits)

lemma time-drop-tm: time (drop-tm n xs) = min n (length xs) + 1
by (induction n xs rule: drop-tm.induct) (simp-all split: nat.splits)

lemma time-drop-tm-le: time (drop-tm n xs) ≤ n + 1
by (simp add: time-drop-tm)

6.4.3 (@)

```
fun append-tm :: 'a list ⇒ 'a list ⇒ 'a list tm where
append-tm [] ys =1 return ys
| append-tm (x # xs) ys =1 do {
  r ← append-tm xs ys;
  return (x # r)
}
```

lemma val-append-tm[*simp*, *val-simp*]: val (append-tm xs ys) = append xs ys
by (induction xs ys rule: append-tm.induct) simp-all

lemma time-append-tm[*simp*]: time (append-tm xs ys) = length xs + 1
by (induction xs ys rule: append-tm.induct) simp-all

6.4.4 fold

```
fun fold-tm where
fold-tm f [] s =1 return s
| fold-tm f (x # xs) s =1 do {
  r ← f x s;
  fold-tm f xs r
}
```

lemma val-fold-tm[*simp*, *val-simp*]: val (fold-tm f xs s) = fold (λx y. val (f x y))
xs s
by (induction xs s rule: fold-tm.induct; simp)

lemma time-fold-tm-Cons: time (fold-tm (λx y. return (x # y)) xs s) = length xs
+ 1
by (induction xs arbitrary: s; simp)

6.4.5 rev

definition *rev-tm* **where** *rev-tm* *xs* = 1 *fold-tm* ($\lambda x y. \text{return } (x \# y)$) *xs* []

lemma *val-rev-tm*[*simp*, *val-simp*]: *val* (*rev-tm* *xs*) = *rev* *xs*
by (*induction* *xs*; *simp* *add*: *rev-tm-def* *fold-Cons-rev*)

lemma *time-rev-tm-le*[*simp*]: *time* (*rev-tm* *xs*) = *length* *xs* + 2
unfolding *rev-tm-def* **using** *time-fold-tm-Cons* **by** *auto*

6.4.6 replicate

fun *replicate-tm* :: *nat* \Rightarrow 'a \Rightarrow 'a *list* *tm* **where**
replicate-tm 0 *x* = 1 *return* []
| *replicate-tm* (*Suc* *n*) *x* = 1 *do* {
 r \leftarrow *replicate-tm* *n* *x*;
 return (*x* # *r*)
}

lemma *val-replicate-tm*[*simp*, *val-simp*]: *val* (*replicate-tm* *n* *x*) = *replicate* *n* *x*
by (*induction* *n* *x* *rule*: *replicate-tm.induct*) *simp-all*

lemma *time-replicate-tm*: *time* (*replicate-tm* *n* *x*) = *n* + 1
by (*induction* *n* *x* *rule*: *replicate-tm.induct*) *simp-all*

6.4.7 length

fun *gen-length-tm* :: *nat* \Rightarrow 'a *list* \Rightarrow *nat* *tm* **where**
gen-length-tm *n* [] = 1 *return* *n*
| *gen-length-tm* *n* (*x* # *xs*) = 1 *gen-length-tm* (*Suc* *n*) *xs*

lemma *val-gen-length-tm*[*simp*, *val-simp*]: *val* (*gen-length-tm* *n* *xs*) = *List.gen-length* *n* *xs*
by (*induction* *n* *xs* *rule*: *gen-length-tm.induct*) (*simp-all* *add*: *List.gen-length-def*)

lemma *time-gen-length-tm*[*simp*]: *time* (*gen-length-tm* *n* *xs*) = *length* *xs* + 1
by (*induction* *n* *xs* *rule*: *gen-length-tm.induct*) *simp-all*

definition *length-tm* :: 'a *list* \Rightarrow *nat* *tm* **where**
length-tm *xs* = *gen-length-tm* 0 *xs*

lemma *val-length-tm*[*simp*, *val-simp*]: *val* (*length-tm* *xs*) = *length* *xs*
by (*simp* *add*: *length-tm-def* *length-code*)

lemma *time-length-tm*[*simp*]: *time* (*length-tm* *xs*) = *length* *xs* + 1
by (*simp* *add*: *length-tm-def*)

6.4.8 List.null

fun *null-tm* :: 'a *list* \Rightarrow *bool* *tm* **where**

null-tm [] =1 return True
 | *null-tm* (x # xs) =1 return False

lemma *val-null-tm*[simp, val-simp]: val (*null-tm* xs) = List.null xs
 by (cases xs; simp add: List.null-def)

lemma *time-null-tm*[simp]: time (*null-tm* xs) = 1
 by (cases xs; simp)

6.4.9 butlast

fun *butlast-tm* :: 'a list ⇒ 'a list tm **where**
butlast-tm [] =1 return []
 | *butlast-tm* (x # xs) =1 do {
 b ← *null-tm* xs;
 if b then return [] else do {
 r ← *butlast-tm* xs;
 return (x # r)
 }
 }

lemma *val-butlast-tm*[simp, val-simp]: val (*butlast-tm* xs) = butlast xs
 by (induction xs rule: *butlast-tm.induct*) (simp-all add: List.null-def)

lemma *time-butlast-tm*: time (*butlast-tm* xs) = 2 * (length xs - 1) + 1 + of-bool
 (length xs ≥ 1)
 by (induction xs rule: *butlast-tm.induct*) (auto simp: List.null-def not-less-eq-eq)

lemma *time-butlast-tm-le*: time (*butlast-tm* xs) ≤ 2 * length xs + 1
 unfolding *time-butlast-tm* by (cases xs; simp)

6.4.10 map

fun *map-tm* :: ('a ⇒ 'b tm) ⇒ 'a list ⇒ 'b list tm **where**
map-tm f [] =1 return []
 | *map-tm* f (x # xs) =1 do {
 r ← f x;
 rs ← *map-tm* f xs;
 return (r # rs)
 }

lemma *val-map-tm*[simp, val-simp]: val (*map-tm* f xs) = map (λx. val (f x)) xs
 by (induction f xs rule: *map-tm.induct*) simp-all

lemma *time-map-tm*: time (*map-tm* f xs) = (∑ i ← xs. time (f i)) + length xs + 1
 by (induction f xs rule: *map-tm.induct*) (simp-all)

lemma *time-map-tm-constant*:
 assumes $\bigwedge i. i \in \text{set } xs \implies \text{time } (f i) = c$

shows $\text{time} (\text{map-tm } f \text{ } xs) = (c + 1) * \text{length } xs + 1$
proof –
have $\text{time} (\text{map-tm } f \text{ } xs) = (\sum i \leftarrow xs. \text{time} (f i)) + \text{length } xs + 1$
by (*simp add: time-map-tm*)
also have $\dots = (\sum i \leftarrow xs. c) + \text{length } xs + 1$
using *assms iffD2[OF map-eq-conv, of xs]* **by** *metis*
also have $\dots = c * \text{length } xs + \text{length } xs + 1$
using *sum-list-triv[of c xs]* **by** *simp*
finally show *?thesis* **by** *simp*
qed

lemma *time-map-tm-bounded*:
assumes $\bigwedge i. i \in \text{set } xs \implies \text{time} (f i) \leq c$
shows $\text{time} (\text{map-tm } f \text{ } xs) \leq (c + 1) * \text{length } xs + 1$
proof –
have $\text{time} (\text{map-tm } f \text{ } xs) = (\sum i \leftarrow xs. \text{time} (f i)) + \text{length } xs + 1$
by (*simp add: time-map-tm*)
also have $\dots \leq (\sum i \leftarrow xs. c) + \text{length } xs + 1$
by (*intro add-mono order.refl sum-list-mono assms*) *argo*
also have $\dots = c * \text{length } xs + \text{length } xs + 1$
using *sum-list-triv[of c xs]* **by** *simp*
finally show *?thesis* **by** *simp*
qed

6.4.11 *foldl*

fun *foldl-tm* :: ('a \Rightarrow 'b \Rightarrow 'a tm) \Rightarrow 'a \Rightarrow 'b list \Rightarrow 'a tm **where**
foldl-tm f a [] =1 return a
| *foldl-tm* f a (x # xs) =1 do {
 r \leftarrow f a x;
 foldl-tm f r xs
}

lemma *val-foldl-tm[simp, val-simp]*: $\text{val} (\text{foldl-tm } f \text{ } a \text{ } xs) = \text{foldl} (\lambda x y. \text{val} (f x y))$
a xs
by (*induction f a xs rule: foldl-tm.induct; simp*)

6.4.12 *concat*

fun *concat-tm* **where**
concat-tm [] =1 return []
| *concat-tm* (x # xs) =1 do {
 r \leftarrow *concat-tm* xs;
 append-tm x r
}

lemma *val-concat-tm[simp, val-simp]*: $\text{val} (\text{concat-tm } xs) = \text{concat } xs$
by (*induction xs; simp*)

lemma *time-concat-tm[simp]*: $\text{time} (\text{concat-tm } xs) = 1 + 2 * \text{length } xs + \text{length} (\text{concat } xs)$

by (*induction xs; simp*)

6.4.13 (!)

fun *nth-tm* **where**

nth-tm ($x \# xs$) 0 =1 return x
| *nth-tm* ($x \# xs$) (Suc i) =1 *nth-tm* xs i
| *nth-tm* [] - =1 undefined

lemma *val-nth-tm[simp, val-simp]*:

assumes $i < \text{length } xs$

shows $\text{val} (\text{nth-tm } xs \ i) = xs \ ! \ i$

using *assms*

proof (*induction i arbitrary: xs*)

case 0

then show ?case **using** *length-greater-0-conv[of xs] neq-Nil-conv[of xs]* **by** *auto*

next

case (Suc i)

then obtain $x \ xs'$ **where** $xsr: xs = x \# xs'$ **by** (*meson Suc-lessE length-Suc-conv*)

then have $i < \text{length } xs'$ **using** *Suc.prem*s **by** *simp*

from *Suc.IH[OF this]* **show** ?case **unfolding** xsr **by** *simp*

qed

lemma *time-nth-tm[simp]*:

assumes $i < \text{length } xs$

shows $\text{time} (\text{nth-tm } xs \ i) = i + 1$

using *assms*

proof (*induction i arbitrary: xs*)

case 0

then show ?case **using** *length-greater-0-conv[of xs] neq-Nil-conv[of xs]* **by** *auto*

next

case (Suc i)

then obtain $x \ xs'$ **where** $xsr: xs = x \# xs'$ **by** (*meson Suc-lessE length-Suc-conv*)

then have $i < \text{length } xs'$ **using** *Suc.prem*s **by** *simp*

from *Suc.IH[OF this]* **show** ?case **unfolding** xsr **by** *simp*

qed

6.4.14 zip

fun *zip-tm* :: ' a list \Rightarrow ' b list \Rightarrow (' $a \times b$) list *tm* **where**

zip-tm xs [] =1 return []

| *zip-tm* [] ys =1 return []

| *zip-tm* ($x \# xs$) ($y \# ys$) =1 do { $rs \leftarrow \text{zip-tm } xs \ ys$; return ($(x, y) \# rs$) }

lemma *val-zip-tm[simp, val-simp]*: $\text{val} (\text{zip-tm } xs \ ys) = \text{zip } xs \ ys$

by (*induction xs ys rule: zip-tm.induct; simp*)

lemma *time-zip-tm[simp]*: $\text{time} (\text{zip-tm } xs \ ys) = \min (\text{length } xs) (\text{length } ys) + 1$

by (induction xs ys rule: zip-tm.induct; simp)

6.4.15 map2

definition map2-tm where

```
map2-tm f xs ys =1 do {  
  xys ← zip-tm xs ys;  
  map-tm (λ(x,y). f x y) xys  
}
```

lemma val-map2-tm[simp, val-simp]: val (map2-tm f xs ys) = map2 (λx y. val (f x y)) xs ys

unfolding map2-tm-def by (simp split: prod.splits)

lemma time-map2-tm-bounded:

assumes length xs = length ys

assumes $\bigwedge x y. x \in \text{set } xs \implies y \in \text{set } ys \implies \text{time } (f x y) \leq c$

shows time (map2-tm f xs ys) $\leq (c + 2) * \text{length } xs + 3$

proof –

have time (map2-tm f xs ys) = length xs + 2 + time (map-tm (λ(x, y). f x y) (zip xs ys))

unfolding map2-tm-def by (simp add: assms)

also have ... $\leq \text{length } xs + 2 + ((c + 1) * \text{length } (\text{zip } xs \text{ } ys) + 1)$

apply (intro add-mono order.refl time-map-tm-bounded)

using assms by (auto split: prod.splits elim: in-set-zipE)

also have ... = $(c + 2) * \text{length } xs + 3$

using assms by simp

finally show ?thesis .

qed

6.4.16 upt

function upt-tm where

```
upt-tm i j =1 do {  
  b ← less-nat-tm i j;  
  (if b then do {  
    rs ← upt-tm (Suc i) j;  
    return (i # rs)  
  } else return [] )  
}
```

by pat-completeness auto

termination by (relation Wellfounded.measure (λ(i, j). j - i)) simp-all

declare upt-tm.simps[simp del]

lemma val-upt-tm[simp, val-simp]: val (upt-tm i j) = [i..<j]

apply (induction i j rule: upt-tm.induct)

subgoal for i j

by (cases i < j; simp add: upt-tm.simps[of i j] upt-conv-Cons)

done

lemma time-upt-tm-le: time (upt-tm i j) $\leq (j - i) * (2 * j + 3) + 2 * j + 2$

```

proof (induction i j rule: upt-tm.induct)
  case (1 i j)
  then show ?case
  proof (cases i < j)
    case True
    then have time (upt-tm i j) = (2 * i + 3) + time (upt-tm (Suc i) j)
    unfolding upt-tm.simps[of i j] tm-time.simps by (simp add: time-less-nat-tm)
    also have ... ≤ (2 * j + 3) + ((j - Suc i) * (2 * j + 3) + 2 * j + 2)
    apply (intro add-mono mult-le-mono order.refl)
    subgoal using True by simp
    subgoal using 1 True by simp
    done
    also have ... = (j - Suc i + 1) * (2 * j + 3) + 2 * j + 2
    by simp
    also have j - Suc i + 1 = (j - i)
    using True by simp
    finally show ?thesis .
  next
  case False
  then show ?thesis by (simp add: upt-tm.simps[of i j] time-less-nat-tm)
qed
qed

```

```

lemma time-upt-tm-le': time (upt-tm i j) ≤ 2 * j * j + 5 * j + 2
  apply (intro order.trans[OF time-upt-tm-le[of i j]])
  apply (estimation estimate: diff-le-self)
  by (simp add: add-mult-distrib2)

```

6.5 Syntactic sugar

```

consts equal-tm :: 'a ⇒ 'a ⇒ bool tm
adhoc-overloading equal-tm equal-nat-tm
adhoc-overloading equal-tm equal-bool-tm

```

```

consts plus-tm :: 'a ⇒ 'a ⇒ 'a tm
adhoc-overloading plus-tm plus-nat-tm

```

```

consts times-tm :: 'a ⇒ 'a ⇒ 'a tm
adhoc-overloading times-tm times-nat-tm

```

```

consts power-tm :: 'a ⇒ nat ⇒ 'a tm
adhoc-overloading power-tm power-nat-tm

```

```

consts minus-tm :: 'a ⇒ 'a ⇒ 'a tm
adhoc-overloading minus-tm minus-nat-tm

```

```

consts less-tm :: 'a ⇒ 'a ⇒ bool tm
adhoc-overloading less-tm less-nat-tm

```

consts *less-eq-tm* :: 'a ⇒ 'a ⇒ bool tm
adhoc-overloading *less-eq-tm* *less-eq-nat-tm*

consts *divide-tm* :: 'a ⇒ 'a ⇒ 'a tm
adhoc-overloading *divide-tm* *divide-nat-tm*

consts *mod-tm* :: 'a ⇒ 'a ⇒ 'a tm
adhoc-overloading *mod-tm* *mod-nat-tm*

bundle *main-tm-syntax*

begin

notation *equal-tm* (**infixl** =_t 51)
notation *Not-tm* (¬_t - [40] 40)
notation *conj-tm* (**infixr** ∧_t 35)
notation *disj-tm* (**infixr** ∨_t 30)
notation *append-tm* (**infixr** @_t 65)
notation *plus-tm* (**infixl** +_t 65)
notation *times-tm* (**infixl** *_t 70)
notation *power-tm* (**infixr** ^_t 80)
notation *minus-tm* (**infixl** -_t 65)
notation *less-tm* (**infix** <_t 50)
notation *less-eq-tm* (**infix** ≤_t 50)
notation *mod-tm* (**infixl** mod_t 70)
notation *divide-tm* (**infixl** div_t 70)
notation *dvd-tm* (**infix** dvd_t 50)

end

bundle *no-main-tm-syntax*

begin

no-notation *equal-tm* (**infixl** =_t 51)
no-notation *Not-tm* (¬_t - [40] 40)
no-notation *conj-tm* (**infixr** ∧_t 35)
no-notation *disj-tm* (**infixr** ∨_t 30)
no-notation *append-tm* (**infixr** @_t 65)
no-notation *plus-tm* (**infixl** +_t 65)
no-notation *times-tm* (**infixl** *_t 70)
no-notation *power-tm* (**infixr** ^_t 80)
no-notation *minus-tm* (**infixl** -_t 65)
no-notation *less-tm* (**infix** <_t 50)
no-notation *less-eq-tm* (**infix** ≤_t 50)
no-notation *mod-tm* (**infixl** mod_t 70)
no-notation *divide-tm* (**infixl** div_t 70)
no-notation *dvd-tm* (**infix** dvd_t 50)

end

unbundle *main-tm-syntax*

end

7 Representations

7.1 Abstract Representations

```
theory Abstract-Representations
  imports Main
begin
```

Idea: some type $'a$ is represented non-uniquely by some type $'b$. The function f produces a unique representant.

```
locale abstract-representation =
  fixes from-type ::  $'a \Rightarrow 'b$ 
  fixes to-type ::  $'b \Rightarrow 'a$ 
  fixes f ::  $'b \Rightarrow 'b$ 
  assumes to-from:  $to\text{-}type \circ from\text{-}type = id$ 
  assumes from-to:  $from\text{-}type \circ to\text{-}type = f$ 
begin
```

```
lemma to-from-elem[simp]:  $to\text{-}type (from\text{-}type\ x) = x$ 
  using to-from by (metis comp-apply id-apply)
lemma from-to-elem:  $from\text{-}type (to\text{-}type\ x) = f\ x$ 
  using from-to by (metis comp-apply)
```

```
lemma f-idem:  $f \circ f = f$ 
proof –
  have  $f \circ f = from\text{-}type \circ to\text{-}type \circ from\text{-}type \circ to\text{-}type$ 
    using from-to by fastforce
  also have  $\dots = from\text{-}type \circ to\text{-}type$ 
    using to-from by (simp add: rewriteR-comp-comp)
  finally show ?thesis using from-to by simp
qed
```

```
corollary f-idem-elem[simp]:  $f (f\ x) = f\ x$ 
  using f-idem by (metis comp-apply)
```

```
lemma f-from:  $f \circ from\text{-}type = from\text{-}type$ 
proof –
  have  $f \circ from\text{-}type = from\text{-}type \circ to\text{-}type \circ from\text{-}type$ 
    using from-to by simp
  also have  $\dots = from\text{-}type$ 
    using to-from by (simp add: rewriteR-comp-comp)
  finally show ?thesis .
qed
```

```
corollary f-from-elem[simp]:  $f (from\text{-}type\ x) = from\text{-}type\ x$ 
  using f-from by (metis comp-apply)
```

```
lemma to-f:  $to\text{-}type \circ f = to\text{-}type$ 
proof –
  have  $to\text{-}type \circ f = to\text{-}type \circ from\text{-}type \circ to\text{-}type$ 
```

using *from-to* by *fastforce*
 also have ... = *to-type* using *to-from* by *simp*
 finally show *?thesis* .
 qed

corollary *to-f-elem[simp]*: *to-type* (f x) = *to-type* x
 using *to-f* by (*metis comp-apply*)

lemma *f-fixed-point-iff*: $f x = x \longleftrightarrow (\exists y. x = \text{from-type } y)$
proof
 assume $f x = x$
 then show $\exists y. x = \text{from-type } y$ using *from-to-elem* by *metis*
next
 assume $\exists y. x = \text{from-type } y$
 then obtain *y* where $x = \text{from-type } y$ by *blast*
 then show $f x = x$ by *simp*
 qed

lemma *f-fixed-point-iff'*: $f x = x \longleftrightarrow x = \text{from-type } (\text{to-type } x)$
 using *from-to* by *auto*

lemma *range-f-range-from*: $\text{range } f = \text{range } \text{from-type}$
proof (*standard*; *standard*)
 fix *x*
 assume $x \in \text{range } f$
 then obtain *x'* where $x = f x'$ by *blast*
 then have $f x = x$ by *simp*
 then show $x \in \text{range } \text{from-type}$ using *f-fixed-point-iff* by *blast*
next
 fix *x*
 assume $x \in \text{range } \text{from-type}$
 then obtain *y* where $x = \text{from-type } y$ by *blast*
 then have $f x = x$ using *f-fixed-point-iff* by *simp*
 then show $x \in \text{range } f$ by (*metis rangeI*)
 qed

lemma *to-eq-iff-f-eq*: $\text{to-type } x = \text{to-type } y \longleftrightarrow f x = f y$
proof
 show $\text{to-type } x = \text{to-type } y \implies f x = f y$ using *from-to-elem[symmetric]* by *simp*
next
 show $f x = f y \implies \text{to-type } x = \text{to-type } y$ using *to-f-elem* by *metis*
 qed

lemma *from-inj*: *inj from-type*
 using *to-from* by (*metis inj-on-id inj-on-imageI2*)

end

lemma *from-to-f-criterion*:

```

assumes  $to\text{-}type \circ from\text{-}type = id$ 
assumes  $f \circ from\text{-}type = from\text{-}type$ 
assumes  $\bigwedge x y. to\text{-}type\ x = to\text{-}type\ y \implies f\ x = f\ y$ 
shows  $from\text{-}type \circ to\text{-}type = f$ 
proof
  fix  $x$ 
  have  $to\text{-}type\ (from\text{-}type\ (to\text{-}type\ x)) = to\text{-}type\ x$ 
    using  $assms(1)$  by  $(metis\ comp\text{-}apply\ id\text{-}apply)$ 
  hence  $f\ (from\text{-}type\ (to\text{-}type\ x)) = f\ x$ 
    using  $assms(3)$  by  $metis$ 
  hence  $from\text{-}type\ (to\text{-}type\ x) = f\ x$ 
    using  $assms(2)$  by  $(metis\ comp\text{-}apply)$ 
  thus  $(from\text{-}type \circ to\text{-}type)\ x = f\ x$ 
    by  $(metis\ comp\text{-}apply)$ 
qed

end

```

7.2 Abstract Representations 2

```

theory Abstract-Representations-2
  imports Main
begin

```

Idea: a subset *represented-set* of some type *'a* is represented non-uniquely by some type *'b*.

```

locale abstract-representation-2 =
  fixes  $from\text{-}type :: 'a \Rightarrow 'b$ 
  fixes  $to\text{-}type :: 'b \Rightarrow 'a$ 
  fixes  $represented\text{-}set :: 'a\ set$ 
  assumes  $to\text{-}from: \bigwedge x. x \in represented\text{-}set \implies to\text{-}type\ (from\text{-}type\ x) = x$ 
  assumes  $to\text{-}type\text{-}in\text{-}represented\text{-}set: \bigwedge y. to\text{-}type\ y \in represented\text{-}set$ 
begin

```

```

definition reduce where
   $reduce\ x \equiv from\text{-}type\ (to\text{-}type\ x)$ 

```

```

abbreviation reduced where
   $reduced\ x \equiv reduce\ x = x$ 

```

```

lemma reduce-reduce[simp]:  $reduced\ (reduce\ x)$ 
  unfolding reduce-def
  by  $(simp\ add: to\text{-}from\ to\text{-}type\text{-}in\text{-}represented\text{-}set)$ 

```

```

definition representations where
   $representations \equiv from\text{-}type\ \text{'represented-set}$ 

```

```

lemma range-reduce:  $representations = range\ reduce$ 
  unfolding representations-def reduce-def

```

```

image-def
apply (intro equalityI subsetI)
subgoal for  $x$ 
proof –
  assume  $x \in \{y. \exists x \in \text{represented-set}. y = \text{from-type } x\}$ 
  then have  $\exists y \in \text{represented-set}. x = \text{from-type } y$  by simp
  then obtain  $y$  where  $x = \text{from-type } y$   $y \in \text{represented-set}$  by blast
  then have  $\text{to-type } x = y$  using to-from by simp
  then have  $x = \text{from-type } (\text{to-type } x)$  using  $\langle x = \text{from-type } y \rangle$  by simp
  then show ?thesis by blast
qed
subgoal for  $x$ 
  using to-type-in-represented-set by blast
done

corollary reduced-from-type[simp]:  $x \in \text{represented-set} \implies \text{reduced } (\text{from-type } x)$ 
  using range-reduce representations-def reduce-reduce by force

lemma to-type-reduce:  $\text{to-type } (\text{reduce } x) = \text{to-type } x$ 
  unfolding reduce-def
  by (simp add: to-from to-type-in-represented-set)

lemma reduced-iff:  $\text{reduced } x \iff (\exists y \in \text{represented-set}. x = \text{from-type } y)$ 
  apply standard
  subgoal
    using reduce-def to-type-in-represented-set by metis
  subgoal
    by fastforce
  done

lemma to-eq-iff-f-eq:  $\text{to-type } x = \text{to-type } y \iff \text{reduce } x = \text{reduce } y$ 
proof
  show  $\text{to-type } x = \text{to-type } y \implies \text{reduce } x = \text{reduce } y$  unfolding reduce-def by
simp
  next
    show  $\text{reduce } x = \text{reduce } y \implies \text{to-type } x = \text{to-type } y$  using to-type-reduce by
metis
  qed

lemma from-inj: inj-on from-type represented-set
  unfolding inj-on-def
  apply standard+
  subgoal for  $x$   $y$ 
    using to-from[of x, symmetric] to-from[of y] by simp
  done

corollary from-bij-betw: bij-betw from-type represented-set representations
  unfolding representations-def
  using from-inj

```

```

by (simp add: inj-on-imp-bij-betw)

lemma correctness-to-from:
  fixes h :: 'a ⇒ 'a ⇒ 'a
  fixes g :: 'b ⇒ 'b ⇒ 'b
  assumes  $\bigwedge x y. \text{to-type } (g x y) = h (\text{to-type } x) (\text{to-type } y)$ 
  shows  $\bigwedge x y. x \in \text{represented-set} \implies y \in \text{represented-set} \implies \text{reduce } (g (\text{from-type } x) (\text{from-type } y)) = \text{from-type } (h x y)$ 
  proof -
    fix x y
    assume  $x \in \text{represented-set } y \in \text{represented-set}$ 
    have  $\text{reduce } (g (\text{from-type } x) (\text{from-type } y)) = \text{from-type } (\text{to-type } (g (\text{from-type } x) (\text{from-type } y)))$ 
      unfolding reduce-def by simp
    also have  $\dots = \text{from-type } (h (\text{to-type } (\text{from-type } x)) (\text{to-type } (\text{from-type } y)))$ 
      using assms by simp
    also have  $\dots = \text{from-type } (h x y)$ 
      using to-from  $\langle x \in \text{represented-set} \rangle \langle y \in \text{represented-set} \rangle$  by simp
    finally show  $\text{reduce } (g (\text{from-type } x) (\text{from-type } y)) = \text{from-type } (h x y)$  .
  qed

end

lemma from-to-f-criterion:
  assumes  $\bigwedge x. x \in \text{represented-set} \implies \text{to-type } (\text{from-type } x) = x$ 
  assumes  $\bigwedge x. x \in \text{represented-set} \implies f (\text{from-type } x) = \text{from-type } x$ 
  assumes  $\bigwedge x y. \text{to-type } x = \text{to-type } y \implies f x = f y$ 
  assumes  $\bigwedge y. \text{to-type } y \in \text{represented-set}$ 
  shows  $\bigwedge x. \text{from-type } (\text{to-type } x) = f x$ 
  proof -
    fix x
    have  $\text{to-type } (\text{from-type } (\text{to-type } x)) = \text{to-type } x$ 
      using assms(1) assms(4) by simp
    hence  $f (\text{from-type } (\text{to-type } x)) = f x$ 
      using assms(3) by metis
    thus  $\text{from-type } (\text{to-type } x) = f x$ 
      using assms(2) assms(4) by simp
  qed

end
theory Nat-LSBF
  imports Main ../Preliminaries/Karatsuba-Sum-Lemmas Abstract-Representations
  HOL-Library.Log-Nat
begin

```

8 Representing *nat* in LSBF

In this theory, a representation of *nat* is chosen and simple algorithms implemented thereon.

lemma *list-isolate-nth*: $i < \text{length } xs \implies \exists xs1\ xs2. xs = xs1 @ (xs ! i) \# xs2 \wedge \text{length } xs1 = i$
using *id-take-nth-drop* **by** *fastforce*

lemma *list-is-replicate-iff*: $xs = \text{replicate } (\text{length } xs) x \longleftrightarrow (\forall i \in \{0..<\text{length } xs\}. xs ! i = x)$

proof

assume $1: xs = \text{replicate } (\text{length } xs) x$
show $\forall i \in \{0..<\text{length } xs\}. xs ! i = x$
using 1 *nth-replicate*[of - length xs x] **by** *auto*

next

assume $\forall i \in \{0..<\text{length } xs\}. xs ! i = x$
then have $\forall i \in \{0..<\text{length } xs\}. xs ! i = (\text{replicate } (\text{length } xs) x) ! i$
using *nth-replicate* **by** *auto*
then show $xs = \text{replicate } (\text{length } xs) x$
using *nth-equalityI*[of xs replicate (length xs) x] **by** *simp*

qed

lemma *list-is-replicate-iff2*: $xs = \text{replicate } (\text{length } xs) x \longleftrightarrow \text{set } xs = \{x\} \vee xs = []$
by (*metis empty-replicate length-0-conv replicate-eqI set-replicate singleton-iff*)

lemma *set-bool-list*: $\text{set } xs \subseteq \{\text{True}, \text{False}\}$
by *auto*

lemma *bool-list-is-replicate-if*:

assumes $a \notin \text{set } xs$ **shows** $xs = \text{replicate } (\text{length } xs) (\neg a)$

proof (*intro iffD2*[OF *list-is-replicate-iff2*])

from *assms* *set-bool-list* **have** $\text{set } xs \subseteq \{\neg a\}$ **by** *fastforce*
then have $\text{set } xs = \{\neg a\} \vee \text{set } xs = \{\}$ **by** (*meson subset-singletonD*)
then show $\text{set } xs = \{\neg a\} \vee xs = []$ **by** *simp*

qed

lemma *bit-strong-decomp-2*: $\exists ys\ zs. xs = ys @ a \# zs \implies \exists ys' n. xs = ys' @ a \# (\text{replicate } n (\neg a))$

proof –

assume $\exists ys\ zs. xs = ys @ a \# zs$
then have $a \in \text{set } xs$ **by** *auto*
from *split-list-last*[OF *this*] **obtain** $ys\ zs$ **where** $xs = ys @ a \# zs$ $a \notin \text{set } zs$ **by** *blast*
from *this*(2) **have** $zs = \text{replicate } (\text{length } zs) (\neg a)$
by (*intro bool-list-is-replicate-if*)
with $\langle xs = ys @ a \# zs \rangle$ **show** *?thesis* **by** *blast*

qed

lemma *bit-strong-decomp-1*: $\exists ys\ zs. xs = ys @ a \# zs \implies \exists ys' n. xs = (\text{replicate } n (\neg a)) @ ys'$

$n (\neg a) @ a \# ys'$

proof –

assume $\exists ys zs. xs = ys @ a \# zs$

then obtain $ys zs$ **where** $xs = ys @ a \# zs$ **by** *blast*

then have $rev xs = rev zs @ [a] @ rev ys$ **by** *simp*

then obtain $n ys'$ **where** $rev xs = ys' @ [a] @ replicate n (\neg a)$

using *bit-strong-decomp-2*[*of rev xs a*] **by** *auto*

then have $xs = replicate n (\neg a) @ [a] @ rev ys'$

by (*metis append-assoc rev-append rev-replicate rev-rev-ident rev-singleton-conv*)

thus *?thesis* **by** *auto*

qed

8.1 Type definition

type-synonym *nat-lsbf* = *bool list*

8.2 Conversions

fun *eval-bool* :: *bool* \Rightarrow *nat* **where**

eval-bool *True* = 1

| *eval-bool* *False* = 0

lemma *eval-bool-is-of-bool*[*simp*]: *eval-bool* = *of-bool*

by *auto*

lemma *eval-bool-leq-1*: *eval-bool* $a \leq 1$

by (*cases a*) *simp-all*

lemma *eval-bool-inj*: *eval-bool* $a = eval-bool b \implies a = b$

by (*cases a*; *cases b*) *simp-all*

fun *to-nat* :: *nat-lsbf* \Rightarrow *nat* **where**

to-nat [] = 0

| *to-nat* ($x \# xs$) = (*eval-bool* x) + 2 * *to-nat* xs

fun *from-nat* :: *nat* \Rightarrow *nat-lsbf* **where**

from-nat 0 = []

| *from-nat* $x = (if\ x\ mod\ 2 = 0\ then\ False\ else\ True) \# (from-nat\ (x\ div\ 2))$

value *from-nat* 103

value *to-nat* (*from-nat* 103)

lemma *to-nat-from-nat*[*simp*]: *to-nat* (*from-nat* x) = x

proof (*induction x* *rule: less-induct*)

case (*less x*)

consider $x = 0$ | $x > 0$ **by** *auto*

then show *?case*

proof (*cases*)

case 1

then show *?thesis* **by** *simp*

next
case 2
then have $to\text{-}nat\ (from\text{-}nat\ x) = eval\text{-}bool\ (if\ x\ mod\ 2 = 0\ then\ False\ else\ True) + 2 * to\text{-}nat\ (from\text{-}nat\ (x\ div\ 2))$
by $(metis\ from\text{-}nat.\ elims\ nat\text{-}less\text{-}le\ to\text{-}nat.\ simps(2))$
also have $... = (x\ mod\ 2) + 2 * to\text{-}nat\ (from\text{-}nat\ (x\ div\ 2))$
by simp
also have $... = (x\ mod\ 2) + 2 * (x\ div\ 2)$
using less 2 by simp
also have $... = x$ **by simp**
finally show $?thesis$.
qed
qed

lemma to-nat-explicitly: $to\text{-}nat\ xs = (\sum\ i \leftarrow [0..<length\ xs].\ eval\text{-}bool\ (xs\ !\ i) * 2^i)$

proof $(induction\ xs\ rule:\ to\text{-}nat.\ induct)$

case 1
then show $?case$ **by simp**

next

case $(2\ x\ xs)$
let $?xs = \lambda i.\ eval\text{-}bool\ ((x\ \#\ xs)\ !\ i)$
have $(\sum\ i \leftarrow [0..<length\ (x\ \#\ xs)].\ ?xs\ i * 2^i)$
 $= ?xs\ 0 + (\sum\ i \leftarrow [1..<length\ (x\ \#\ xs)].\ ?xs\ i * 2^i)$
by $(simp\ add:\ upt\text{-}rec)$
also have $... = ?xs\ 0 + (\sum\ i \leftarrow [0..<length\ xs].\ ?xs\ (i + 1) * 2^{(i + 1)})$
using list-sum-index-shift[of - length xs 0 $\lambda i.\ ?xs\ i * 2^i$] by simp
also have $... = ?xs\ 0 + 2 * (\sum\ i \leftarrow [0..<length\ xs].\ ?xs\ (i + 1) * 2^i)$
by $(simp\ add:\ sum\text{-}list\text{-}const\text{-}mult\ mult.\ left\text{-}commute)$
also have $... = ?xs\ 0 + 2 * to\text{-}nat\ xs$
using 2 by simp
also have $... = to\text{-}nat\ (x\ \#\ xs)$ **by simp**
finally show $?case$ **by simp**

qed

lemma to-nat-app: $to\text{-}nat\ (xs\ @\ ys) = to\text{-}nat\ xs + (2^{length\ xs}) * to\text{-}nat\ ys$
by $(induction\ xs)\ auto$

lemma to-nat-length-upper-bound: $to\text{-}nat\ xs \leq 2^{length\ xs} - 1$

proof $(induction\ xs)$

case Nil
then show $?case$ **by simp**

next

case $(Cons\ a\ xs)$
then have $to\text{-}nat\ (a\ \#\ xs) = eval\text{-}bool\ a + 2 * to\text{-}nat\ xs$ **by simp**
also have $... \leq eval\text{-}bool\ a + 2 * (2^{length\ xs} - 1)$ **using Cons.IH by simp**
also have $... \leq 1 + 2 * (2^{length\ xs} - 1)$ **using eval-bool-leq-1[of a] by simp**
also have $... = 1 + (2^{length\ xs + 1} - 1 - 1)$ **by simp**


```

also have ... = 2 ^ (length xs + 1) - 1
  apply (intro add-diff-inverse-nat)
  using power-increasing[of 1 length xs + 1 2::nat]
  by (simp add: add.commute)
finally show ?case by simp
qed
lemma to-nat-length-bound: to-nat xs < 2 ^ length xs
  using to-nat-length-upper-bound[of xs]
  using le-eq-less-or-eq by fastforce
lemma to-nat-length-lower-bound: to-nat (xs @ [True]) ≥ 2 ^ length xs
  by (induction xs) auto

lemma to-nat-replicate-false[simp]: to-nat (replicate n False) = 0
  by (induction n) simp-all

lemma to-nat-one-bit[simp]: to-nat (replicate n False @ [True]) = 2 ^ n
  by (simp add: to-nat-app)

lemma to-nat-replicate-true[simp]: to-nat (replicate n True) = 2 ^ n - 1
proof (induction n)
  case 0
  then show ?case by simp
next
  case (Suc n)
  have 2 ^ (Suc n) ≥ (2 :: nat) by simp
  hence 1: 2 ^ (Suc n) - 1 ≥ (1 :: nat) by linarith
  have to-nat (replicate (Suc n) True) = 1 + 2 * to-nat (replicate n True)
    by simp
  also have ... = 1 + 2 * (2 ^ n - 1)
    using Suc.IH by simp
  also have ... = 2 ^ (Suc n) - 1
    using le-add-diff-inverse[of 1 2 ^ (Suc n) - 1]
    using 1 by simp
  finally show ?case .
qed

lemma to-nat xs = 0 ↔ (∃ n. xs = replicate n False)
proof
  show to-nat xs = 0 ⇒ ∃ n. xs = replicate n False
  proof (induction xs)
    case Nil
    then show ?case by simp
  next
    case (Cons a xs)
    then have a = False to-nat xs = 0 by auto
    then obtain n where xs = replicate n False using Cons.IH by auto
    hence a # xs = replicate (Suc n) False using ⟨a = False⟩ by simp
    then show ?case by blast
  qed

```

show $\exists n. xs = \text{replicate } n \text{ False} \implies \text{to-nat } xs = 0$
using *to-nat-replicate-false* **by** *auto*
qed

lemma *to-nat-app-replicate[simp]*: $\text{to-nat } (xs @ \text{replicate } n \text{ False}) = \text{to-nat } xs$
by (*induction xs*) *auto*

lemma *change-bit-ineq*: $\text{length } xs = \text{length } ys \implies \text{to-nat } (xs @ \text{False} \# zs) < \text{to-nat } (ys @ \text{True} \# zs)$

proof –
assume $\text{length } xs = \text{length } ys$
have $\text{to-nat } (xs @ \text{False} \# zs) = \text{to-nat } xs + 2^{\text{length } xs + 1} * \text{to-nat } zs$
using *to-nat-app-replicate[of xs 1]* *to-nat-app* **by** *simp*
also have $\dots \leq 2^{\text{length } xs} - 1 + 2^{\text{length } xs + 1} * \text{to-nat } zs$
using *to-nat-length-upper-bound[of xs]* **by** *linarith*
also have $\dots < 2^{\text{length } xs} + 2^{\text{length } xs + 1} * \text{to-nat } zs$ **by** *simp*
also have $\dots = 2^{\text{length } ys} + 2^{\text{length } ys + 1} * \text{to-nat } zs$
using $\langle \text{length } xs = \text{length } ys \rangle$ **by** *simp*
also have $\dots \leq \text{to-nat } (ys @ [\text{True}]) + 2^{\text{length } ys + 1} * \text{to-nat } zs$
using *to-nat-length-lower-bound[of ys]* **by** *simp*
also have $\dots = \text{to-nat } (ys @ \text{True} \# zs)$
using *to-nat-app* **by** *simp*
finally show *?thesis* .
qed

lemma *to-nat-ineq-imp-False-bit*: $\text{to-nat } xs < 2^{\text{length } xs} - 1 \implies \exists ys zs. xs = ys @ \text{False} \# zs$

proof (*rule ccontr*)
assume $\nexists ys zs. xs = ys @ \text{False} \# zs$
then have $\forall i \in \{0..<\text{length } xs\}. xs ! i = \text{True}$
by (*metis(full-types) atLeastLessThan-iff in-set-conv-decomp-first in-set-conv-nth*)
then have $xs = \text{replicate } (\text{length } xs) \text{ True}$ **using** *list-is-replicate-iff* **by** *fast*
then have $\text{to-nat } xs = 2^{\text{length } xs} - 1$ **using** *to-nat-replicate-true* **by** *metis*
thus $\text{to-nat } xs < 2^{\text{length } xs} - 1 \implies \text{False}$ **by** *simp*
qed

lemma *to-nat-bound-to-length-bound*: $\text{to-nat } xs \geq 2^n \implies \text{length } xs \geq n + 1$

proof (*rule ccontr*)
assume $\text{to-nat } xs \geq 2^n$
assume $\neg n + 1 \leq \text{length } xs$
then have $n \geq \text{length } xs$ **by** *simp*
then have $\text{to-nat } xs \geq 2^{\text{length } xs}$ **using** $\langle \text{to-nat } xs \geq 2^n \rangle$
using *power-increasing le-trans one-le-numeral* **by** *meson*
then show *False* **using** *to-nat-length-bound[of xs]* **by** *simp*
qed

lemma *to-nat-drop-take*: $\text{to-nat } xs = \text{to-nat } (\text{take } k \text{ } xs) + 2^k * \text{to-nat } (\text{drop } k \text{ } xs)$

proof –

have $xs = take\ k\ xs\ @\ drop\ k\ xs$ **by** *simp*
then have $to_nat\ xs = to_nat\ (take\ k\ xs) + 2^{\wedge}(length\ (take\ k\ xs)) * to_nat\ (drop\ k\ xs)$
using *to-nat-app by metis*
also have $2^{\wedge}(length\ (take\ k\ xs)) * to_nat\ (drop\ k\ xs) = 2^{\wedge}k * to_nat\ (drop\ k\ xs)$
by *(cases length xs < k) simp-all*
finally show *?thesis .*
qed

lemma *to-nat-take*: $to_nat\ (take\ k\ xs) = to_nat\ xs\ mod\ 2^{\wedge}k$
proof –
have $to_nat\ xs = to_nat\ (take\ k\ xs) + 2^{\wedge}k * to_nat\ (drop\ k\ xs)$
by *(simp add: to-nat-drop-take)*
then have $to_nat\ xs\ mod\ 2^{\wedge}k = to_nat\ (take\ k\ xs)\ mod\ 2^{\wedge}k$ **by** *simp*
moreover have $to_nat\ (take\ k\ xs) < 2^{\wedge}k$
using *to-nat-length-bound[of take k xs] length-take[of k xs]*
by *(metis add-leD1 leI min-absorb2 min-def to-nat-bound-to-length-bound)*
ultimately show *?thesis by simp*
qed

lemma *to-nat-drop*: $to_nat\ (drop\ k\ xs) = to_nat\ xs\ div\ 2^{\wedge}k$
proof –
have $to_nat\ xs = to_nat\ xs\ mod\ 2^{\wedge}k + 2^{\wedge}k * to_nat\ (drop\ k\ xs)$
using *to-nat-drop-take[of xs k] to-nat-take[of k xs] by argo*
then have $to_nat\ xs\ div\ 2^{\wedge}k = to_nat\ (drop\ k\ xs)$
by *(metis add.right-neutral bits-mod-div-trivial div-mult-self2 power-not-zero zero-neq-numeral)*
thus *?thesis by rule*
qed

lemma *to-nat-nth-True-bound*:
assumes $i < length\ xs$
assumes $xs\ !\ i = True$
shows $to_nat\ xs \geq 2^{\wedge}i$
proof –
from *assms* **have** $xs = (take\ i\ xs\ @\ [True])\ @\ drop\ (Suc\ i)\ xs$
using *id-take-nth-drop by fastforce*
then show $to_nat\ xs \geq 2^{\wedge}i$
using *to-nat-app[of - drop (Suc i) xs] to-nat-length-lower-bound[of take i xs] <i < length xs>*
by *(metis append-eq-conv-conj le-add1 le-eq-less-or-eq list-isolate-nth trans-less-add1)*
qed

8.3 Truncating and filling

fun *truncate-reversed* :: *bool list* \Rightarrow *bool list* **where**
truncate-reversed [] = []
| *truncate-reversed* (x#xs) = (if x then x#xs else *truncate-reversed* xs)

definition *truncate* :: *nat-lsbf* \Rightarrow *nat-lsbf* **where**

truncate xs = *rev (truncate-reversed (rev xs))*

abbreviation *truncated* **where** *truncated x* \equiv *truncate x* = *x*

lemma *truncate-reversed-eqI[simp]*: *xs* = (*replicate n False*) @ *ys* \implies *truncate-reversed xs* = *truncate-reversed ys*

by (*induction n arbitrary: xs ys*) *auto*

corollary *truncate-eqI[simp]*: *xs* = *ys* @ (*replicate n False*) \implies *truncate xs* = *truncate ys*

by (*simp add: truncate-def*)

lemma *replicate-truncate-reversed*: $\exists n.$ (*replicate n False*) @ *truncate-reversed xs* = *xs*

proof (*induction xs*)

case *Nil*

then show ?*case* **by** *simp*

next

case (*Cons a xs*)

then obtain *n* **where** *1: replicate n False @ truncate-reversed xs* = *xs* **by** *blast*

hence *a # xs* = *a # replicate n False @ truncate-reversed xs* **by** *simp*

show ?*case*

proof (*cases a*)

case *True*

then have *truncate-reversed (a # xs)* = *a # xs* **by** *simp*

also have ... = *replicate 0 False @ a # xs* **by** *simp*

finally show ?*thesis* **by** *simp*

next

case *False*

then have *truncate-reversed (a # xs)* = *truncate-reversed xs* **by** *simp*

hence *replicate (Suc n) False @ truncate-reversed (a # xs)* = *False # replicate n False @ truncate-reversed xs*

by *simp*

with *1 False* **have** *replicate (Suc n) False @ truncate-reversed (a # xs)* = *a # xs* **by** *simp*

then show ?*thesis* **by** *blast*

qed

qed

corollary *truncate-replicate*: $\exists n.$ *truncate xs @ (replicate n False)* = *xs*

proof –

from *replicate-truncate-reversed*[*of rev xs*]

obtain *n* **where** *replicate n False @ truncate-reversed (rev xs)* = *rev xs* **by** *blast*

hence *rev (truncate-reversed (rev xs)) @ rev (replicate n False)* = *xs*

using *rev-append[symmetric, of truncate-reversed (rev xs) replicate n False]*

using *rev-rev-ident*[*of xs*]

by *simp*

hence *truncate xs @ replicate n False* = *xs* **by** (*simp add: truncate-def*)

thus ?*thesis* **by** *blast*

qed

lemma *decompose-trailing-zeros*: $xs = \text{truncate } xs \ @ \ (\text{replicate } (\text{length } xs - \text{length } (\text{truncate } xs)) \ \text{False})$
using *truncate-replicate*[of *xs*]
by (*metis add-diff-cancel-left' length-append length-replicate*)

lemma *truncate-reversed-length-ineq*: $\text{length } (\text{truncate-reversed } xs) \leq \text{length } xs$
by (*induction xs*) *simp-all*

lemma *truncate-length-ineq*: $\text{length } (\text{truncate } xs) \leq \text{length } xs$
by (*metis Nat-LSBF.truncate-def length-rev truncate-reversed-length-ineq*)

lemma *truncate-reversed-fixed-point-iff*: $\text{truncate-reversed } x = x \iff (x = [] \vee \text{hd } x = \text{True})$
proof (*induction x*)
case *Nil*
then show *?case* **by** *simp*
next
case (*Cons a x*)
then have $(a \# x = [] \vee \text{hd } (a \# x) = \text{True}) = a$ **by** *simp*
moreover have $a \implies \text{truncate-reversed } (a \# x) = a \# x$ **by** *simp*
moreover have $\neg a \implies \text{truncate-reversed } (a \# x) = \text{truncate-reversed } x$ **by** *simp*
hence $\neg a \implies \text{length } (\text{truncate-reversed } (a \# x)) \leq \text{length } x$
using *truncate-reversed-length-ineq*[of *x*] **by** *simp*
hence $\neg a \implies \text{truncate-reversed } (a \# x) \neq (a \# x)$
using *neq-if-length-neq*[of *a#x x*] **by** *force*
ultimately show *?case* **by** *simp*
qed

lemma *truncated-iff*: $\text{truncated } x \iff (x = [] \vee \text{last } x = \text{True})$
proof –
have $\text{truncated } x \iff \text{truncate-reversed } (\text{rev } x) = \text{rev } x$
by (*simp add: truncate-def rev-swap*)
also have $\dots \iff \text{rev } x = [] \vee \text{hd } (\text{rev } x) = \text{True}$
using *truncate-reversed-fixed-point-iff*[of *rev x*].
also have $\dots \iff x = [] \vee \text{last } x = \text{True}$
by (*simp add: hd-rev*)
finally show *?thesis*.
qed

lemma *hd-truncate-reversed*: $\text{truncate-reversed } xs \neq [] \implies \text{hd } (\text{truncate-reversed } xs) = \text{True}$
proof (*induction xs*)
case *Nil*
then show *?case* **by** *simp*
next
case (*Cons a xs*)
show *?case*
proof (*rule ccontr*)

```

assume 1: hd (truncate-reversed (a # xs)) ≠ True
then have a = False by auto
with 1 have hd (truncate-reversed xs) ≠ True by simp
hence truncate-reversed xs = [] using Cons.IH by blast
hence truncate-reversed (a # xs) = [] using ⟨a = False⟩ by simp
thus False using Cons.prems by simp
qed
qed

```

```

lemma last-truncate: truncate xs ≠ [] ⇒ last (truncate xs) = True
using hd-truncate-reversed last-rev by (auto simp: truncate-def)

```

```

lemma truncate-truncate[simp]: truncate (truncate xs) = truncate xs
using truncated-iff[of truncate xs] last-truncate by auto

```

```

lemma truncate-reversed-Nil-iff: truncate-reversed xs = [] ↔ (∃ n. xs = replicate n False)

```

```

proof
show truncate-reversed xs = [] ⇒ ∃ n. xs = replicate n False
proof (induction xs)
  case Nil
  then show ?case by simp
next
  case (Cons a xs)
  then have a = False truncate-reversed (a#xs) = truncate-reversed xs
  by (auto split: if-splits)
  then obtain n where xs = replicate n False using Cons by auto
  hence a # xs = replicate (Suc n) False using ⟨a = False⟩ by simp
  thus ?case by blast
qed
next
show ∃ n. xs = replicate n False ⇒ truncate-reversed xs = []
proof (induction xs)
  case Nil
  then show ?case by simp
next
  case (Cons a xs)
  then show ?case
  by (metis Cons-replicate-eq truncate-reversed.simps(2))
qed
qed

```

```

lemma truncate-Nil-iff: truncate xs = [] ↔ (∃ n. xs = replicate n False)
using truncate-reversed-Nil-iff[of rev xs]
by (auto simp: truncate-def) (metis rev-replicate rev-rev-ident)

```

```

corollary truncate-neq-Nil: truncate xs ≠ [] ⇒ ∃ ys zs. xs = ys @ True # zs
using truncate-Nil-iff[of xs]

```

by (*metis (full-types) hd-Cons-tl hd-truncate-reversed replicate-truncate-reversed truncate-reversed-Nil-iff*)

lemma *truncate-Cons*: $\text{truncate } (a \# xs) = (\text{if } \neg a \wedge (\text{truncate } xs = []) \text{ then } [] \text{ else } a \# \text{truncate } xs)$

proof (*cases truncate xs = []*)

case *True*

then obtain *n* **where** $xs = \text{replicate } n \text{ False}$ **using** *truncate-Nil-iff* **by** *blast*

then have $\text{truncate } (a \# xs) = \text{truncate } [a]$ **by** *simp*

then show *?thesis* **using** *True* **by** (*simp add: truncate-def*)

next

case *False*

then obtain *ys n* **where** $xs = ys @ \text{True} \# (\text{replicate } n \text{ False})$

using *truncate-neq-Nil[of xs] bit-strong-decomp-2[of xs True]* **by** *auto*

then have $\text{truncate } xs = ys @ [\text{True}]$ **by** (*auto simp: truncate-def*)

moreover have $\text{truncate } (a \# xs) = a \# ys @ [\text{True}]$

using $\langle xs = ys @ \text{True} \# (\text{replicate } n \text{ False}) \rangle$ **by** (*auto simp: truncate-def*)

ultimately show *?thesis* **by** *simp*

qed

lemma *truncate-eq-Cons*: $\text{truncate } xs = \text{truncate } ys \implies \text{truncate } (a \# xs) = \text{truncate } (a \# ys)$

using *truncate-Cons* **by** *simp*

lemma *truncate-as-take*: $\bigwedge xs. \exists n. \text{truncate } xs = \text{take } n \text{ } xs$

using *truncate-replicate append-eq-conv-conj* **by** *blast*

lemma *to-nat-zero-iff*: $\text{to-nat } xs = 0 \iff \text{truncate } xs = []$

proof (*induction xs*)

case *Nil*

then show *?case* **by** (*simp add: truncate-def*)

next

case (*Cons a xs*)

have $\text{to-nat } (a \# xs) = 0 \iff (\text{eval-bool } a = 0 \wedge \text{to-nat } xs = 0)$ **by** *simp*

also have $\dots \iff (a = \text{False} \wedge \text{to-nat } xs = 0)$ **using** *eval-bool-inj[of a False]* **by** *auto*

also have $\dots \iff (a = \text{False} \wedge \text{truncate } xs = [])$ **using** *Cons.IH* **by** *simp*

also have $\dots \iff (\text{truncate } (a \# xs) = [])$ **using** *truncate-Cons* **by** *simp*

finally show *?case* .

qed

lemma *to-nat-eq-imp-truncate-eq*: $\text{to-nat } xs = \text{to-nat } ys \implies \text{truncate } xs = \text{truncate } ys$

proof (*induction xs arbitrary: ys*)

case *Nil*

then show *?case* **using** *to-nat-zero-iff* **by** (*simp add: truncate-def*)

next

case (*Cons a xs*)

show *?case*

```

proof (cases ys = [])
  case True
    then have to-nat ys = 0 by simp
    hence to-nat (a # xs) = 0 using Cons.prem by simp
    with ⟨to-nat ys = 0⟩ show truncate (a # xs) = truncate ys
      using to-nat-zero-iff[of a # xs] to-nat-zero-iff[of ys] by simp
  next
    case False
      then obtain b zs where ys = b # zs by (meson neq-Nil-conv)
      then have to-nat (a # xs) = to-nat (b # zs) using Cons.prem by simp
      then have 1: eval-bool a + 2 * to-nat xs = eval-bool b + 2 * to-nat zs by simp
      then have eval-bool a = eval-bool b
      by (metis add-cancel-right-left double-not-eq-Suc-double eval-bool.elims plus-1-eq-Suc)
      hence a = b using eval-bool-inj by simp
      from 1 have to-nat xs = to-nat zs
        using ⟨eval-bool a = eval-bool b⟩ by auto
      hence truncate xs = truncate zs using Cons.IH by simp
      hence truncate (a # xs) = truncate (b # zs) using ⟨a = b⟩
        using truncate-eq-Cons[of xs zs a] by simp
      thus ?thesis using ⟨ys = b # zs⟩ by simp
  qed
qed

```

```

lemma truncate-from-nat[simp]: truncate (from-nat x) = from-nat x
  unfolding truncated-iff
  by (induction x rule: from-nat.induct) auto

```

```

lemma truncate-and-length-eq-imp-eq:
  assumes truncate xs = truncate ys length xs = length ys
  shows xs = ys
  proof –
    obtain n where 1: xs = truncate xs @ replicate n False
      by (metis truncate-replicate)
    then have 2: length xs = length (truncate xs) + n
      by (metis length-append length-replicate)
    obtain m where 3: ys = truncate ys @ replicate m False
      by (metis truncate-replicate)
    then have length ys = length (truncate ys) + m
      by (metis length-append length-replicate)
    with 2 assms have n = m by simp
    with 1 3 assms show ?thesis by algebra
  qed

```

```

lemma nat-lsbf-eqI:
  assumes to-nat xs = to-nat ys
  assumes length xs = length ys
  shows xs = ys
  using assms
  using to-nat-eq-imp-truncate-eq truncate-and-length-eq-imp-eq by blast

```


interpretation *nat-lsb*: *abstract-representation from-nat to-nat truncate*

proof

show $to\text{-}nat \circ from\text{-}nat = id$
using *to-nat-from-nat comp-apply* **by** *fastforce*

next

show $from\text{-}nat \circ to\text{-}nat = truncate$
using *from-to-f-criterion*[*of to-nat from-nat truncate*]
using *to-nat-from-nat truncate-from-nat to-nat-eq-imp-truncate-eq*
using *comp-apply*
by *fastforce*

qed

lemma *truncated-Cons-imp-truncated-tl*: $truncated (x \# xs) \implies truncated xs$

using *truncated-iff* **by** *fastforce*

definition *fill where* $fill\ n\ xs = xs @ replicate\ (n - length\ xs)\ False$

lemma *to-nat-fill*[*simp*]: $to\text{-}nat (fill\ n\ xs) = to\text{-}nat\ xs$

by (*simp add: fill-def*)

lemma *length-fill*[*intro*]: $length\ xs \leq n \implies length (fill\ n\ xs) = n$

by (*simp add: fill-def*)

lemma *take-id*: $length\ xs = k \implies take\ k\ xs = xs$

by *simp*

lemma *fill-id*: $length\ xs \geq k \implies fill\ k\ xs = xs$

unfolding *fill-def* **by** *simp*

lemma *length-fill'*: $length (fill\ n\ xs) = max\ n (length\ xs)$

by (*simp add: fill-def*)

lemma *length-fill-max*[*simp*]:

$length (fill (max (length\ xs) (length\ ys))\ xs) = max (length\ xs) (length\ ys)$

$length (fill (max (length\ xs) (length\ ys))\ ys) = max (length\ xs) (length\ ys)$

by (*intro length-fill, simp*)⁺

lemma *truncate-fill*: $truncate (fill\ k\ xs) = truncate\ xs$

by (*simp add: fill-def*)

lemma *fill-truncate*: $length\ xs \leq k \implies fill\ k (truncate\ xs) = fill\ k\ xs$

proof –

assume $length\ xs \leq k$

obtain n **where** *n-def*: $xs = truncate\ xs @ replicate\ n\ False$

using *truncate-replicate* **by** *metis*

then have $length\ xs = length (truncate\ xs) + n$ **by** (*metis length-append length-replicate*)

then have $length (truncate\ xs) + n \leq k$ **using** $\langle length\ xs \leq k \rangle$ **by** *simp*

```

from n-def have fill k xs = (truncate xs @ replicate n False) @ replicate (k -
length (truncate xs @ replicate n False)) False
  using fill-def by presburger
  also have ... = truncate xs @ replicate (n + (k - length (truncate xs @ replicate
n False))) False
  by (simp add: replicate-add)
  also have ... = truncate xs @ replicate (n + (k - (length (truncate xs) + n)))
False
  by simp
  also have ... = truncate xs @ replicate (k - (length (truncate xs))) False
  using <length (truncate xs) + n ≤ k> by simp
  also have ... = fill k (truncate xs) by (simp add: fill-def)
  finally show ?thesis by simp
qed

```

```

lemma fill-take-com: fill k (take k xs) = take k (fill k xs)
  using fill-def by fastforce

```

```

lemma to-nat-length-lower-bound-truncated: xs ≠ [] ⇒ truncated xs ⇒ to-nat
xs ≥ 2 ^ (length xs - 1)

```

```

proof -
  assume xs ≠ [] truncated xs
  then obtain xs' where xs = xs' @ [True]
  by (metis(full-types) append-butlast-last-id last-truncate)
  then show ?thesis using to-nat-length-lower-bound[of xs'] by simp
qed

```

```

lemma to-nat-length-bound-truncated: truncated xs ⇒ to-nat xs < 2 ^ n ⇒
length xs ≤ n

```

```

proof (rule ccontr)
  assume truncated xs to-nat xs < 2 ^ n ¬ length xs ≤ n
  show False
  proof (cases xs = [])
    case True
    then show ?thesis using <¬ length xs ≤ n> by simp
  next
    case False
    have length xs ≥ n + 1 using <¬ length xs ≤ n> by simp
    then have to-nat xs ≥ 2 ^ n
      using to-nat-length-lower-bound-truncated[of xs]
      using False <truncated xs>
    by (meson add-le-imp-le-diff dual-order.trans one-le-numeral power-increasing)
    then show ?thesis using <to-nat xs < 2 ^ n> by simp
  qed
qed

```

8.4 Right-shifts

```

definition shift-right :: nat ⇒ nat-lsbf ⇒ nat-lsbf where

```

$shift\text{-}right\ n\ xs = (replicate\ n\ False) @ xs$

lemma *to-nat-shift-right*[simp]: $to\text{-}nat\ (shift\text{-}right\ n\ xs) = 2 \wedge n * to\text{-}nat\ xs$
unfolding *shift-right-def* **using** *to-nat-app* **by** *simp*

lemma *length-shift-right*[simp]: $length\ (shift\text{-}right\ n\ xs) = n + length\ xs$
unfolding *shift-right-def* **by** *simp*

8.5 Subdividing lists

8.5.1 Splitting a list in two blocks

fun *split-at* :: $nat \Rightarrow 'a\ list \Rightarrow 'a\ list \times 'a\ list$ **where**
 $split\text{-}at\ m\ xs = (take\ m\ xs, drop\ m\ xs)$

definition *split* :: $nat\text{-}lsbf \Rightarrow nat\text{-}lsbf \times nat\text{-}lsbf$ **where**
 $split\ xs = (let\ n = length\ xs\ div\ (2::nat)\ in\ split\text{-}at\ n\ xs)$

lemma *app-split*: $split\ xs = (x0, x1) \Longrightarrow xs = x0 @ x1$
unfolding *split-def* *Let-def* **using** *append-take-drop-id*[of $length\ xs\ div\ 2\ xs$] **by** *simp*

lemma *length-split*: $length\ xs\ mod\ 2 = 0 \Longrightarrow split\ xs = (x0, x1) \Longrightarrow length\ x0 = length\ xs\ div\ 2 \wedge length\ x1 = length\ xs\ div\ 2$
unfolding *split-def* **by** *fastforce*

lemma *length-split-le*:
assumes $split\ xs = (x0, x1)$
shows $length\ x0 \leq length\ xs$ **and** $length\ x1 \leq length\ xs$
using *app-split*[*OF* *assms*] **by** *simp-all*

8.5.2 Splitting a list in multiple blocks

subdivide n xs divides the list *xs* into blocks of size *n*.

fun *subdivide* :: $nat \Rightarrow 'a\ list \Rightarrow 'a\ list\ list$ **where**
 $subdivide\ 0\ xs = undefined$
 $| subdivide\ n\ [] = []$
 $| subdivide\ n\ xs = take\ n\ xs \# subdivide\ n\ (drop\ n\ xs)$

value *concat* [[0..<2], [4..<7], [1..<5]]

value *subdivide* 2 [0..<6]
value *subdivide* 3 [0..<6]
value *subdivide* (2 ^ 2) [0..<2 ^ 6]

lemma *concat-subdivide*: $n > 0 \Longrightarrow concat\ (subdivide\ n\ xs) = xs$
by (*induction n xs rule: subdivide.induct*) *simp-all*

lemma *subdivide-step*:

assumes $n > 0$
assumes $xs \neq []$
assumes $length\ xs = n * k$
obtains $ys\ zs$ **where** $xs = ys @ zs$ $length\ ys = n$ $length\ zs = n * (k - 1)$
 $subdivide\ n\ xs = ys \# subdivide\ n\ zs$

proof –

from *assms* **obtain** $a\ xs'$ **where** $xs = a \# xs'$ **using** *list.exhaust* **by** *blast*
from *assms* **have** $k > 0$
using *zero-less-iff-neq-zero* **by** *fastforce*
then **obtain** k' **where** $k = Suc\ k'$ **using** *gr0-implies-Suc* **by** *auto*
then **have** $length\ xs = n + n * k'$ **using** *assms(3)* **by** *simp*
define $ys\ zs$ **where** $ys = take\ n\ xs$ $zs = drop\ n\ xs$
with $\langle length\ xs = n + n * k' \rangle$ **have** $xs = ys @ zs$ $length\ ys = n$ $length\ zs = n * k'$ **by** *simp-all*
moreover **have** $subdivide\ n\ xs = ys \# subdivide\ n\ zs$ **using** *ys-zs-def* *assms(1)*
assms(2) *Suc-diff-1* *subdivide.simps(3)*
 $\langle xs = a \# xs' \rangle$ **by** *metis*
ultimately **show** $(\bigwedge ys\ zs.$
 $xs = ys @ zs \implies$
 $length\ ys = n \implies$
 $length\ zs = n * (k - 1) \implies$
 $subdivide\ n\ xs = ys \# subdivide\ n\ zs \implies thesis) \implies$
 $thesis$
by (*simp add: $\langle k = Suc\ k' \rangle$*)

qed

lemma *subdivide-step'*:

assumes $n > 0$
assumes $xs \neq []$
shows $subdivide\ n\ xs = (take\ n\ xs) \# subdivide\ n\ (drop\ n\ xs)$
using *assms*
by (*cases n; cases xs; simp-all*)

lemma *subdivide-correct*:

assumes $n > 0$
assumes $length\ xs = n * k$
shows $length\ (subdivide\ n\ xs) = k \wedge (x \in set\ (subdivide\ n\ xs) \longrightarrow length\ x = n)$
using *assms*

proof (*induction k arbitrary: xs n x*)

case 0

then **have** $subdivide\ n\ xs = []$ **using** 0 *gr0-conv-Suc* **by** *force*
then **show** *?case* **by** *simp*

next

case $(Suc\ k)$

then **have** $xs \neq []$ **by** *force*
from *subdivide-step*[*OF $\langle n > 0 \rangle$ this $\langle length\ xs = n * Suc\ k \rangle$*] **obtain** $ys\ zs$
where *ys-zs*:
 $xs = ys @ zs$
 $length\ ys = n$

```

    length zs = n * (Suc k - 1)
    subdivide n xs = ys # subdivide n zs
  by blast
  then have length zs = n * k by simp
  note IH = Suc.IH[OF ‹n > 0› this]
  from IH show ?case using ys-zs by simp
qed

lemma nth-nth-subdivide:
  assumes n > 0
  assumes length xs = n * k
  assumes i < k j < n
  shows subdivide n xs ! i ! j = xs ! (i * n + j)
  using assms
proof (induction k arbitrary: xs i)
  case 0
  then show ?case by simp
next
  case (Suc k)
  then have xs ≠ [] by auto
  with Suc subdivide-step obtain ys zs where xs = ys @ zs length ys = n length
  zs = n * (Suc k - 1)
  subdivide n xs = ys # subdivide n zs by blast
  then have length zs = n * k by simp
  show ?case
  proof (cases i)
    case 0
    then have subdivide n xs ! i ! j = ys ! (i * n + j) using ‹subdivide n xs = ys
  # subdivide n zs› by simp
    then show ?thesis using ‹xs = ys @ zs› 0 ‹j < n› ‹length ys = n›
    by (simp add: nth-append)
  next
    case (Suc i')
    then have subdivide n xs ! i ! j = subdivide n zs ! i' ! j
    using ‹subdivide n xs = ys # subdivide n zs› by simp
    also have ... = zs ! (i' * n + j)
    apply (intro Suc.IH[of zs i'])
    subgoal using ‹n > 0› .
    subgoal using ‹length zs = n * k› .
    subgoal using ‹i < Suc k› ‹i = Suc i'› by simp
    subgoal using ‹j < n› .
    done
    also have ... = xs ! (i * n + j)
    using ‹i = Suc i'› ‹xs = ys @ zs› ‹length ys = n›
    by (metis ab-semigroup-add-class.add-ac(1) mult-Suc nth-append-length-plus)
  finally show ?thesis .
  qed
qed

```

```

lemma subdivide-concat:
  assumes  $n > 0$ 
  assumes  $\bigwedge i. i < \text{length } xs \implies \text{length } (xs ! i) = n$ 
  shows  $\text{subdivide } n (\text{concat } xs) = xs$ 
proof (intro iffD1[OF concat-eq-concat-iff])
  show  $\text{concat } (\text{subdivide } n (\text{concat } xs)) = \text{concat } xs$ 
    using concat-subdivide[OF <n > 0>] .
  have  $\text{map } \text{length } xs = \text{replicate } (\text{length } xs) n$ 
    apply (intro replicate-eqI)
    subgoal by simp
    subgoal using assms by (metis in-set-conv-nth length-map nth-map)
  done
  then have  $\text{length } (\text{concat } xs) = \text{length } xs * n$ 
    by (simp add: length-concat sum-list-replicate)
  then show  $\text{length } (\text{subdivide } n (\text{concat } xs)) = \text{length } xs$ 
    apply (intro conjunct1[OF subdivide-correct] <n > 0>) by simp
  show  $\forall (x, y) \in \text{set } (\text{zip } (\text{subdivide } n (\text{concat } xs)) xs). \text{length } x = \text{length } y$ 
proof
  fix  $z$ 
  assume  $a: z \in \text{set } (\text{zip } (\text{subdivide } n (\text{concat } xs)) xs)$ 
  then obtain  $x y$  where  $z = (x, y)$  by fastforce
  from  $a$  obtain  $i$  where  $i < \text{length } xs$   $z = \text{zip } (\text{subdivide } n (\text{concat } xs)) xs ! i$ 
    using  $\langle \text{length } (\text{subdivide } n (\text{concat } xs)) = \text{length } xs \rangle$ 
  by (metis (no-types, lifting) gen-length-def in-set-conv-nth length-code length-zip
min-OR min-add-distrib-left)
  then have  $\text{subdivide } n (\text{concat } xs) ! i = x$   $xs ! i = y$ 
    using  $\langle z = (x, y) \rangle \langle \text{length } (\text{subdivide } n (\text{concat } xs)) = \text{length } xs \rangle$  by simp-all
  then have  $\text{length } x = n$  using  $\langle i < \text{length } xs \rangle \langle \text{length } (\text{subdivide } n (\text{concat } xs))$ 
   $= \text{length } xs \rangle$ 
    using  $\langle \text{length } (\text{concat } xs) = \text{length } xs * n \rangle$ 
     $\langle n > 0 \rangle$  mult.commute[of n length xs]
    by (metis nth-mem subdivide-correct)
  moreover from  $\langle xs ! i = y \rangle \langle i < \text{length } xs \rangle$  have  $\text{length } y = n$  using assms
by blast
  ultimately show case z of  $(x, y) \implies \text{length } x = \text{length } y$  using  $\langle z = (x, y) \rangle$ 
by simp
  qed
qed

```

```

lemma to-nat-subdivide:
  assumes  $n > 0$ 
  assumes  $\text{length } xs = n * k$ 
  shows  $\text{to-nat } xs = (\sum i \leftarrow [0..<k]. \text{to-nat } (\text{subdivide } n xs ! i) * 2 ^ (i * n))$ 
    using assms
proof (induction k arbitrary: xs)
  case 0
  then show ?case by simp
next
  case (Suc k)

```

then have $\text{length } (\text{take } n \text{ } xs) = n \text{ length } (\text{drop } n \text{ } xs) = n * k$ **by** *simp-all*
from *Suc* **have** $xs \neq []$ **by** *auto*
have $(\sum i \leftarrow [0..<Suc \ k]. \text{to-nat } (\text{subdivide } n \text{ } xs ! i) * 2^{\wedge} (i * n))$
 $= \text{to-nat } (\text{subdivide } n \text{ } xs ! 0) * 2^{\wedge} (0 * n) + (\sum i \leftarrow [1..<Suc \ k]. \text{to-nat } (\text{subdivide } n \text{ } xs ! i) * 2^{\wedge} (i * n))$
by (*intro sum-list-split-0*)
also have $\text{subdivide } n \text{ } xs ! 0 = \text{take } n \text{ } xs$
using *Suc* $\langle xs \neq [] \rangle$ *subdivide-step'*[*OF* $\langle 0 < n \rangle \langle xs \neq [] \rangle$] **by** *simp*
also have $(\sum i \leftarrow [1..<Suc \ k]. \text{to-nat } (\text{subdivide } n \text{ } xs ! i) * 2^{\wedge} (i * n))$
 $= (\sum i \leftarrow [0..<k]. \text{to-nat } (\text{subdivide } n \text{ } xs ! (i + 1)) * 2^{\wedge} ((i + 1) * n))$
using *sum-list-index-shift*[*of* $\lambda i. \text{to-nat } (\text{subdivide } n \text{ } xs ! i) * 2^{\wedge} (i * n) \ 1 \ 0 \ k$] **by** *simp*
also have $\dots = (\sum i \leftarrow [0..<k]. \text{to-nat } (\text{subdivide } n \text{ } (\text{drop } n \text{ } xs) ! i) * 2^{\wedge} ((i + 1) * n))$
using *subdivide-step'*[*OF* $\langle 0 < n \rangle \langle xs \neq [] \rangle$] **by** *simp*
also have $\dots = (\sum i \leftarrow [0..<k]. (\text{to-nat } (\text{subdivide } n \text{ } (\text{drop } n \text{ } xs) ! i) * (2^{\wedge} n * 2^{\wedge} (i * n))))$
by (*simp add: power-add*)
also have $\dots = (\sum i \leftarrow [0..<k]. 2^{\wedge} n * (\text{to-nat } (\text{subdivide } n \text{ } (\text{drop } n \text{ } xs) ! i) * 2^{\wedge} (i * n)))$
by (*simp add: mult.left-commute*)
also have $\dots = 2^{\wedge} n * (\sum i \leftarrow [0..<k]. \text{to-nat } (\text{subdivide } n \text{ } (\text{drop } n \text{ } xs) ! i) * 2^{\wedge} (i * n))$
by (*simp add: sum-list-const-mult*)
also have $\dots = 2^{\wedge} n * \text{to-nat } (\text{drop } n \text{ } xs)$
using *Suc.IH*[*OF* $\langle 0 < n \rangle \langle \text{length } (\text{drop } n \text{ } xs) = n * k \rangle$] **by** *argo*
finally have $(\sum i \leftarrow [0..<Suc \ k]. \text{to-nat } (\text{subdivide } n \text{ } xs ! i) * 2^{\wedge} (i * n))$
 $= \text{to-nat } (\text{take } n \text{ } xs) + 2^{\wedge} n * \text{to-nat } (\text{drop } n \text{ } xs)$
by *simp*
also have $\dots = \text{to-nat } (\text{take } n \text{ } xs @ \text{drop } n \text{ } xs)$
by (*simp only: to-nat-app* $\langle \text{length } (\text{take } n \text{ } xs) = n \rangle$)
also have $\dots = \text{to-nat } xs$ **by** *simp*
finally show $\text{to-nat } xs = (\sum i \leftarrow [0..<Suc \ k]. \text{to-nat } (\text{subdivide } n \text{ } xs ! i) * 2^{\wedge} (i * n))$
by *simp*
qed

8.6 The *bitsize* function

bitsize n calculates how many bits are needed in the LSBF encoding of n .

fun *bitsize* :: *nat* \Rightarrow *nat* **where**

bitsize $0 = 0$

| *bitsize* $n = 1 + \text{bitsize } (n \text{ div } 2)$

lemma *bitsize-is-floorlog*: *bitsize* = *floorlog* 2

apply (*intro ext*)

subgoal for n

apply (*induction n rule: bitsize.induct*)

by (*auto simp add: floorlog-eq-zero-iff compute-floorlog*)

done

corollary *bitsize-bitlen*: $\text{int } (\text{bitsize } n) = \text{bitlen } (\text{int } n)$
unfolding *bitsize-is-floorlog bitlen-def* **by** *simp*

lemma *bitsize-eq*: $\text{bitsize } n = \text{length } (\text{from-nat } n)$
proof (*induction n rule: less-induct*)
case (*less n*)
then show *?case*
proof (*cases n = 0*)
case *True*
then show *?thesis* **by** *simp*
next
case *False*
then have *1: bitsize n = 1 + bitsize (n div 2)*
by (*metis bitsize.elims*)
from *False* **have** $\text{length } (\text{from-nat } n) = \text{length } ((\text{if } n \bmod 2 = 0 \text{ then } \text{False} \text{ else } \text{True}) \# \text{from-nat } (n \text{ div } 2))$
by (*metis from-nat.elims*)
also have $\dots = 1 + \text{bitsize } (n \text{ div } 2)$ **using** *less[of n div 2] False* **by** *simp*
finally show $\text{bitsize } n = \text{length } (\text{from-nat } n)$ **using** *1* **by** *simp*
qed
qed

lemma *bitsize-zero-iff*: $\text{bitsize } n = 0 \iff n = 0$
by (*simp add: bitsize-is-floorlog floorlog-eq-zero-iff*)

lemma *truncated-iff'*: $\text{truncated } x \iff \text{length } x = \text{bitsize } (\text{to-nat } x)$
proof
assume *truncated x*
then have $x = \text{from-nat } (\text{to-nat } x)$ **unfolding** *nat-lsb.f.fixed-point-iff'*.
then show $\text{length } x = \text{bitsize } (\text{to-nat } x)$ **unfolding** *bitsize-eq* **by** *simp*
next
assume $\text{length } x = \text{bitsize } (\text{to-nat } x)$
then have $\text{length } x = \text{length } (\text{from-nat } (\text{to-nat } x))$ **unfolding** *bitsize-eq*.
moreover have $\text{to-nat } x = \text{to-nat } (\text{from-nat } (\text{to-nat } x))$ **by** *simp*
ultimately show *truncated x* **unfolding** *nat-lsb.f.fixed-point-iff'*
by (*intro nat-lsb.eqI; argo*)
qed

lemma *bitsize-length*: $\text{bitsize } n \leq k \iff n < 2^k$
unfolding *bitsize-is-floorlog floorlog-le-iff* **by** *simp*

lemma *two-pow-bitsize-pos-bound*: $n > 0 \implies 2^{\text{bitsize } n} \leq 2 * n$
proof –
assume $n > 0$
then have $2^{\text{bitsize } n - 1} \leq n$
using *bitsize-length[of n bitsize n - 1]* **by** *fastforce*
then have $2^{\text{bitsize } n - 1 + 1} \leq 2 * n$ **by** *simp*

also have $\text{bitsize } n - 1 + 1 = \text{bitsize } n$ using $\text{bitsize-zero-iff}[of\ n] \langle n > 0 \rangle$ by *simp*
 finally show *?thesis* .
 qed

lemma *two-pow-bitsize-bound*: $2^{\text{bitsize } n} \leq 2 * n + 1$
 using *two-pow-bitsize-pos-bound*[of *n*] by (cases *n*) *simp-all*

lemma *bitsize-mono*: $n1 \leq n2 \implies \text{bitsize } n1 \leq \text{bitsize } n2$
 unfolding *bitsize-is-floorlog* by (rule *floorlog-mono*)

8.6.1 The next-power-of-2 function

lemma *power-of-2-recursion*: $(\exists k. (n::nat) = 2^k) \longleftrightarrow (n = 1 \vee (n \text{ mod } 2 = 0 \wedge (\exists k. n \text{ div } 2 = 2^k)))$

proof

assume $\exists k. n = 2^k$

then obtain *k* where *k-def*: $n = 2^k$ by *blast*

show $n = 1 \vee (n \text{ mod } 2 = 0 \wedge (\exists k. n \text{ div } 2 = 2^k))$

using *k-def* by (cases *k*) *simp-all*

next

assume $n = 1 \vee (n \text{ mod } 2 = 0 \wedge (\exists k. n \text{ div } 2 = 2^k))$

then consider $n = 1 \mid n \text{ mod } 2 = 0 \wedge (\exists k. n \text{ div } 2 = 2^k)$ by *argo*

then show $\exists k. n = 2^k$

proof *cases*

case 1

then have $n = 2^0$ by *simp*

then show *?thesis* by *blast*

next

case 2

then obtain *k* where $n \text{ div } 2 = 2^k$ by *blast*

with 2 have $n = 2^{\text{Suc } k}$ by *auto*

then show *?thesis* by *blast*

qed

qed

fun *is-power-of-2* :: *nat* \Rightarrow *bool* where

is-power-of-2 0 = *False*

| *is-power-of-2* (*Suc* 0) = *True*

| *is-power-of-2* *n* = $((n \text{ mod } 2 = 0) \wedge \text{is-power-of-2 } (n \text{ div } 2))$

lemma *is-power-of-2-correct*: $\text{is-power-of-2 } n \longleftrightarrow (\exists k. n = 2^k)$

proof (*induction n rule: is-power-of-2.induct*)

case 1

then show *?case* by *simp*

next

case 2

then show *?case* by (*metis is-power-of-2.simps(2) nat-power-eq-Suc-0-iff*)

next

```

case ( $\exists va$ )
let  $?n = \text{Suc} (\text{Suc } va)$ 
have  $\text{is-power-of-2 } ?n = ((?n \text{ mod } 2 = 0) \wedge \text{is-power-of-2 } (?n \text{ div } 2))$ 
  by simp
also have  $\dots = ((?n \text{ mod } 2 = 0) \wedge (\exists k. (?n \text{ div } 2) = 2 \wedge k))$ 
  using  $\exists$  by argo
also have  $\dots = (\exists k. ?n = 2 \wedge k)$ 
  using  $\text{power-of-2-recursion}[of ?n]$  by simp
finally show  $?case$  .
qed

```

```

fun  $\text{next-power-of-2} :: \text{nat} \Rightarrow \text{nat}$  where
 $\text{next-power-of-2 } n = (\text{if } \text{is-power-of-2 } n \text{ then } n \text{ else } 2 \wedge (\text{bitsize } n))$ 

```

```

lemma  $\text{next-power-of-2-lower-bound}$ :  $\text{next-power-of-2 } k \geq k$ 
apply (cases is-power-of-2 k)
subgoal by simp
subgoal premises prems
proof -
  from prems have  $\text{next-power-of-2 } k - 1 = 2 \wedge \text{bitsize } k - 1$  by simp
  also have  $\dots = 2 \wedge (\text{length } (\text{from-nat } k)) - 1$  using  $\text{bitsize-eq}$  by simp
  also have  $\dots \geq k$  using  $\text{to-nat-length-upper-bound}[of \text{from-nat } k]$  by simp
  finally show  $?thesis$  by simp
qed
done

```

```

lemma  $\text{next-power-of-2-upper-bound}$ :
assumes  $k \neq 0$ 
shows  $\text{next-power-of-2 } k \leq 2 * k$ 
apply (cases is-power-of-2 k)
subgoal by simp
subgoal premises prems
proof -
  have  $2 \wedge (\text{length } (\text{from-nat } k) - 1) \leq \text{to-nat } (\text{from-nat } k)$ 
    apply (intro to-nat-length-lower-bound-truncated)
    subgoal using assms by (cases k; simp)
    subgoal by simp
    done
  then have  $2 \wedge \text{length } (\text{from-nat } k) \leq 2 * \text{to-nat } (\text{from-nat } k)$ 
    using assms by (cases k; simp)
  also have  $\dots = 2 * k$  by simp
  also have  $2 \wedge \text{length } (\text{from-nat } k) = \text{next-power-of-2 } k$ 
    using prems bitsize-eq by simp
  finally show  $?thesis$  .
qed
done

```

```

lemma  $\text{next-power-of-2-upper-bound}'$ :  $\text{next-power-of-2 } k \leq 2 * k + 1$ 

```

```

apply (cases k)
subgoal by simp
subgoal using next-power-of-2-upper-bound[of k] by simp
done

```

```

lemma next-power-of-2-is-power-of-2:  $\exists k. \text{next-power-of-2 } n = 2 \wedge k$ 
using is-power-of-2-correct by simp

```

8.7 Addition

```

fun bit-add-carry :: bool  $\Rightarrow$  bool  $\Rightarrow$  bool  $\Rightarrow$  bool  $\times$  bool where
bit-add-carry False False False = (False, False)
| bit-add-carry False False True = (True, False)
| bit-add-carry False True False = (True, False)
| bit-add-carry False True True = (False, True)
| bit-add-carry True False False = (True, False)
| bit-add-carry True False True = (False, True)
| bit-add-carry True True False = (False, True)
| bit-add-carry True True True = (True, True)

```

```

lemma bit-add-carry-correct: bit-add-carry c x y = (a, b)  $\implies$  eval-bool c + eval-bool
x + eval-bool y = eval-bool a + 2 * eval-bool b
by (cases c; cases x; cases y) auto

```

8.7.1 Increment operation

```

fun inc-nat :: nat-lsbf  $\Rightarrow$  nat-lsbf where
inc-nat [] = [True]
| inc-nat (False # xs) = True # xs
| inc-nat (True # xs) = False # (inc-nat xs)

```

```

lemma length-inc-nat': length (inc-nat xs) = length xs + of-bool (to-nat xs + 1  $\geq$ 
2  $\wedge$  length xs)

```

```

proof (induction xs rule: inc-nat.induct)

```

```

case 1

```

```

then show ?case by simp

```

```

next

```

```

case (2 xs)

```

```

then show ?case using to-nat-length-bound[of xs] by simp

```

```

next

```

```

case (3 xs)

```

```

then show ?case by simp

```

```

qed

```

```

lemma length-inc-nat-lower: length (inc-nat xs)  $\geq$  length xs
unfolding length-inc-nat' by simp

```

```

lemma length-inc-nat-upper: length (inc-nat xs)  $\leq$  length xs + 1
unfolding length-inc-nat' by simp

```

lemma *inc-nat-nonempty*: $inc\text{-}nat\ xs \neq []$
by (*induction xs rule: inc-nat.induct*) *simp-all*

lemma *inc-nat-replicate-True*: $inc\text{-}nat\ (replicate\ m\ True) = replicate\ m\ False\ @\ [True]$
by (*induction m*) *simp-all*

lemma *inc-nat-replicate-True-2*: $inc\text{-}nat\ (replicate\ m\ True\ @\ False\ \# ys) = replicate\ m\ False\ @\ True\ \# ys$
by (*induction m*) *simp-all*

lemma *length-inc-nat-iff*: $length\ (inc\text{-}nat\ xs) = length\ xs \iff (\exists\ ys\ zs.\ xs = ys\ @\ False\ \# zs)$
proof (*intro iffI, rule ccontr*)
assume $\nexists\ ys\ zs.\ xs = ys\ @\ False\ \# zs$
then have $\forall i \in \{0..<length\ xs\}.\ xs!i = True$
by (*metis(full-types) atLeastLessThan-iff in-set-conv-nth split-list*)
then have $xs = replicate\ (length\ xs)\ True$
by (*simp only: list-is-replicate-iff*)
then show $length\ (inc\text{-}nat\ xs) = length\ xs \implies False$
using *inc-nat-replicate-True*
by (*metis length-append-singleton length-replicate n-not-Suc-n*)
next
assume $\exists\ ys\ zs.\ xs = ys\ @\ False\ \# zs$
then have $\exists n\ zs'. xs = replicate\ n\ True\ @\ False\ \# zs'$
using *bit-strong-decomp-1* **by** *fastforce*
then show $length\ (inc\text{-}nat\ xs) = length\ xs$
using *inc-nat-replicate-True-2* **by** *fastforce*
qed

lemma *inc-nat-last-bit-True*: $length\ (inc\text{-}nat\ xs) = Suc\ (length\ xs) \implies \exists\ zs.\ inc\text{-}nat\ xs = zs\ @\ [True]$
by (*induction xs rule: inc-nat.induct*) *auto*

lemma *inc-nat-truncated*: $truncated\ xs \implies truncated\ (inc\text{-}nat\ xs)$
proof (*induction xs rule: inc-nat.induct*)
case 1
then show *?case* **using** *truncate-def* **by** *simp*
next
case (2 xs)
then show *?case* **by** (*simp add: truncated-iff*)
next
case (3 xs)
then show *?case* **by** (*simp add: truncated-iff inc-nat-nonempty split: if-splits*)
qed

lemma *inc-nat-correct*: $to\text{-}nat\ (inc\text{-}nat\ xs) = to\text{-}nat\ xs + 1$
by (*induction xs rule: inc-nat.induct*) *simp-all*

```

lemma length-inc-nat:  $\text{length } (\text{inc-nat } xs) = \max (\text{length } xs) (\text{floorlog } 2 (\text{to-nat } xs + 1))$ 
proof (induction xs rule: inc-nat.induct)
  case 1
  then show ?case by (simp add: compute-floorlog)
next
  case (2 xs)
  then show ?case using to-nat-length-bound[of False # xs]
    by (simp add: floorlog-leI)
next
  case (3 xs)
  then have  $\text{length } (\text{inc-nat } (\text{True} \# xs)) = \text{Suc } (\max (\text{length } xs) (\text{floorlog } 2 (\text{Suc } (\text{to-nat } xs))))$ 
    by simp
  also have  $\dots = \max (\text{length } (\text{True} \# xs)) (\text{Suc } (\text{floorlog } 2 (\text{Suc } (\text{to-nat } xs))))$ 
    by simp
  also have  $\dots = \max (\text{length } (\text{True} \# xs)) (\text{floorlog } 2 (2 * \text{Suc } (\text{to-nat } xs)))$ 
    apply (intro arg-cong2[where  $f = \max$ ] refl)
    by (simp add: compute-floorlog)
  finally show ?case by simp
qed

```

8.7.2 Addition with a carry bit

```

fun add-carry ::  $\text{bool} \Rightarrow \text{nat-lsbf} \Rightarrow \text{nat-lsbf} \Rightarrow \text{nat-lsbf}$  where
  add-carry False [] y = y
  | add-carry False x [] = x
  | add-carry True [] y = inc-nat y
  | add-carry True x [] = inc-nat x
  | add-carry c (x#xs) (y#ys) = (let (a, b) = bit-add-carry c x y in a#(add-carry b xs ys))

```

lemma *add-carry-correct*: $\text{to-nat } (\text{add-carry } c \ x \ y) = \text{eval-bool } c + \text{to-nat } x + \text{to-nat } y$

```

proof (induction c x y rule: add-carry.induct)
  case (1 y)
  then show ?case by simp
next
  case (2 v va)
  then show ?case by simp
next
  case (3 y)
  then show ?case using inc-nat-correct by simp
next
  case (4 v va)
  then show ?case using inc-nat-correct by simp
next
  case (5 c x xs y ys)
  define a b where  $a = \text{fst } (\text{bit-add-carry } c \ x \ y)$   $b = \text{snd } (\text{bit-add-carry } c \ x \ y)$ 

```

then have $to_nat (add_carry\ c\ (x\#\!xs)\ (y\#\!ys)) = to_nat (a\ \#\! add_carry\ b\ xs\ ys)$
by (*simp add: case-prod-beta' Let-def*)
also have $\dots = eval_bool\ a + 2 * to_nat (add_carry\ b\ xs\ ys)$ **by** *simp*
also have $\dots = eval_bool\ a + 2 * (eval_bool\ b + to_nat\ xs + to_nat\ ys)$
using *5 a-b-def prod.collapse[of bit-add-carry c x y]* **by** *algebra*
also have $\dots = eval_bool\ c + eval_bool\ x + eval_bool\ y + 2 * (to_nat\ xs + to_nat\ ys)$
using *bit-add-carry-correct a-b-def* **by** (*simp add: prod-eq-iff*)
also have $\dots = eval_bool\ c + to_nat (x\#\!xs) + to_nat (y\#\!ys)$ **by** *simp*
finally show *?case .*
qed

lemma *length-add-carry'*: $length (add_carry\ c\ xs\ ys) = max (length\ xs) (length\ ys) + of_bool (to_nat\ xs + to_nat\ ys + of_bool\ c \geq 2 \wedge max (length\ xs) (length\ ys))$

proof (*induction c xs ys rule: add-carry.induct*)

case (*1 y*)

then show *?case* **using** *to-nat-length-bound[of y]* **by** *simp*

next

case (*2 v va*)

then show *?case*

using *to-nat-length-bound[of va]* **by** *simp*

next

case (*3 y*)

then show *?case* **by** (*simp add: length-inc-nat'*)

next

case (*4 v va*)

then show *?case* **by** (*simp add: length-inc-nat'*)

next

case (*5 c x xs y ys*)

have $l: 2 \wedge Suc\ a \leq 2 * b + 1 \iff 2 \wedge Suc\ a \leq 2 * b$ **for** $a\ b :: nat$

by *fastforce*

obtain $a\ b$ **where** *bit-add-carry c x y = (a, b)* **by** *fastforce*

then have $add_carry\ c\ (x\ \#\! xs)\ (y\ \#\! ys) = a\ \#\! (add_carry\ b\ xs\ ys)$ **by** *simp*

then have $length (add_carry\ c\ (x\ \#\! xs)\ (y\ \#\! ys)) = 1 + max (length\ xs) (length\ ys) + of_bool (2 \wedge max (length\ xs) (length\ ys) \leq to_nat\ xs + to_nat\ ys + of_bool\ b)$

using *5.IH[OF <bit-add-carry c x y = (a, b)>[symmetric] refl]* **by** (*simp only: length-Cons*)

also have $\dots = max (length (x\ \#\! xs)) (length (y\ \#\! ys)) + of_bool (2 \wedge max (length\ xs) (length\ ys) \leq to_nat\ xs + to_nat\ ys + of_bool\ b)$

by *simp*

also have $\dots = max (length (x\ \#\! xs)) (length (y\ \#\! ys)) + of_bool (2 \wedge max (length (x\ \#\! xs)) (length (y\ \#\! ys)) \leq to_nat (x\ \#\! xs) + to_nat (y\ \#\! ys) + of_bool\ c)$

proof (*intro arg-cong2[where f = (+)] refl arg-cong[where f = of-bool]*)

have $to_nat (x\ \#\! xs) + to_nat (y\ \#\! ys) + of_bool\ c =$

$2 * to_nat\ xs + 2 * to_nat\ ys + of_bool\ x + of_bool\ y + of_bool\ c$

by *simp*

also have ... = 2 * to-nat xs + 2 * to-nat ys + of-bool a + 2 * of-bool b
using bit-add-carry-correct[OF ‹bit-add-carry c x y = (a, b)›] **by** simp
finally have r: to-nat (x # xs) + to-nat (y # ys) + of-bool c =
show (2 ^ max (length xs) (length ys) ≤ to-nat xs + to-nat ys + of-bool b) =
(2 ^ max (length (x # xs)) (length (y # ys)) ≤ to-nat (x # xs) + to-nat (y #
ys) + of-bool c)
unfolding r **using** l[of max (length xs) (length ys) to-nat xs + to-nat ys +
of-bool b]
by auto
qed
finally show ?case .
qed

lemma length-add-carry: length (add-carry c xs ys) = max (max (length xs) (length
ys)) (floorlog 2 (of-bool c + to-nat xs + to-nat ys))
proof (induction c xs ys rule: add-carry.induct)
case (1 y)
then show ?case **using** to-nat-length-bound[of y]
by (simp add: floorlog-leI)
next
case (2 v va)
then show ?case **using** to-nat-length-bound[of v # va]
by (simp add: floorlog-leI)
next
case (3 y)
then show ?case **by** (simp add: length-inc-nat)
next
case (4 v va)
then show ?case **by** (simp add: length-inc-nat)
next
case (5 c x xs y ys)
obtain a b **where** bit-add-carry c x y = (a, b) **by** fastforce
then have add-carry c (x # xs) (y # ys) = a # (add-carry b xs ys) **by** simp
then have length (add-carry c (x # xs) (y # ys)) = Suc (max (max (length xs)
(length ys)) (floorlog 2 (of-bool b + to-nat xs + to-nat ys)))
using 5 ‹bit-add-carry c x y = (a, b)› **by** (simp only: length-Cons)
also have ... = max (max (length (x # xs)) (length (y # ys))) (1 + floorlog 2
(of-bool b + to-nat xs + to-nat ys))
by simp
also have ... = max (max (length (x # xs)) (length (y # ys))) (floorlog 2 (of-bool
c + to-nat (x # xs) + to-nat (y # ys)))
proof (cases of-bool a + 2 * (of-bool b + to-nat xs + to-nat ys) > 0)
case True
then show ?thesis
proof (intro arg-cong2[where f = max] refl)
have floorlog 2 (of-bool c + to-nat (x # xs) + to-nat (y # ys)) =
floorlog 2 ((of-bool c + of-bool x + of-bool y) + 2 * (to-nat xs + to-nat
ys))
by simp

```

    also have ... = floorlog 2 ((of-bool a + 2 * of-bool b) + 2 * (to-nat xs +
to-nat ys))
    using bit-add-carry-correct[OF ‹bit-add-carry c x y = (a, b)›] by simp
    also have ... = floorlog 2 (of-bool a + 2 * (of-bool b + to-nat xs + to-nat ys))
    by simp
    also have ... = 1 + floorlog 2 (of-bool b + to-nat xs + to-nat ys)
    using compute-floorlog[of 2 of-bool a + 2 * (of-bool b + to-nat xs + to-nat
ys)] True
    by simp
    finally show ... = floorlog 2 (of-bool c + to-nat (x # xs) + to-nat (y # ys))
by simp
qed
next
case False
then have 01: of-bool a = 0 of-bool b = 0 to-nat xs = 0 to-nat ys = 0 by
simp-all
then have 02: of-bool c = 0 of-bool x = 0 of-bool y = 0
using bit-add-carry-correct[OF ‹bit-add-carry c x y = (a, b)›] by simp-all
from 01 02 show ?thesis by (simp add: floorlog-def)
qed
finally show ?case .
qed

```

lemma *length-add-carry-lower*: $\text{length} (\text{add-carry } c \text{ } xs \text{ } ys) \geq \max (\text{length } xs) (\text{length } ys)$
unfolding *length-add-carry'* **by** *simp*

lemma *length-add-carry-upper*: $\text{length} (\text{add-carry } c \text{ } xs \text{ } ys) \leq \max (\text{length } xs) (\text{length } ys) + 1$
unfolding *length-add-carry'* **by** *simp*

lemma *add-carry-last-bit-True*: $\text{length} (\text{add-carry } c \text{ } xs \text{ } ys) = \max (\text{length } xs) (\text{length } ys) + 1 \implies \exists zs. \text{add-carry } c \text{ } xs \text{ } ys = zs \text{ } @ \text{ } [True]$

proof (*induction c xs ys rule: add-carry.induct*)

```

case (1 y)
then show ?case by simp
next
case (2 v va)
then show ?case by simp
next
case (3 y)
then show ?case by (simp add: inc-nat-last-bit-True)
next
case (4 v va)
then show ?case by (simp add: inc-nat-last-bit-True)
next
case (5 c x xs y ys)
obtain a b where bit-add-carry c x y = (a, b) by fastforce
then have 1: add-carry c (x # xs) (y # ys) = a # (add-carry b xs ys)

```



```

    by simp
  from 5 have length (add-carry b xs ys) = max (length (x # xs)) (length (y #
ys))
    using ⟨bit-add-carry c x y = (a, b)⟩ by auto
  also have ... = max (length xs) (length ys) + 1 by simp
  finally obtain zs where add-carry b xs ys = zs @ [True] using 5 ⟨bit-add-carry
c x y = (a, b)⟩
    by presburger
  then show ?case using 1 by simp
qed

```

```

lemma add-carry-com: add-carry c xs ys = add-carry c ys xs
  apply (intro nat-lsbf-eqI)
  subgoal by (simp add: add-carry-correct)
  subgoal by (simp only: length-add-carry' max.commute add.commute)
  done

```

```

lemma add-carry-rNil[simp]: add-carry True y [] = inc-nat y
  by (cases y; simp)
lemma add-carry-rNil-nocarry[simp]: add-carry False y [] = y
  by (cases y; simp)

```

```

lemma add-carry-True-inc-nat:
  add-carry True xs ys = inc-nat (add-carry False xs ys) ∧
  add-carry True xs ys = add-carry False (inc-nat xs) ys ∧
  add-carry True xs ys = add-carry False xs (inc-nat ys)
proof (induction xs arbitrary: ys)

```

```

  case Nil
  then show ?case
    apply (intro conjI)
    subgoal by simp
    subgoal
      apply (cases ys)
      subgoal by simp
      subgoal for a ys'
        by (cases a) simp-all
      done
    subgoal by simp
  done

```

```

next
  case (Cons a xs)
  then show ?case
    apply (cases a; cases ys)
    subgoal by simp
    subgoal for b ys'
      apply (cases b)
      subgoal by fastforce
      subgoal by simp

```

```

done
subgoal by (simp add: add-carry-com)
subgoal for b ys'
  apply (cases b)
  subgoal by fastforce
  subgoal by simp
done
done
qed

```

lemma *inc-nat-add-carry*:

```

inc-nat (add-carry c xs ys) = add-carry c (inc-nat xs) ys ∧
inc-nat (add-carry c xs ys) = add-carry c xs (inc-nat ys)

```

proof (cases c)

case *True*

then have

```

add-carry c (inc-nat xs) ys = inc-nat (add-carry False (inc-nat xs) ys)
add-carry c xs (inc-nat ys) = inc-nat (add-carry False xs (inc-nat ys))
using add-carry-True-inc-nat by simp-all

```

moreover have

```

add-carry False (inc-nat xs) ys = inc-nat (add-carry False xs ys)
using add-carry-True-inc-nat[of xs ys] by argo

```

moreover have $\text{add-carry False xs (inc-nat ys) = inc-nat (add-carry False xs ys)}$

using *add-carry-True-inc-nat*[of xs ys] **by** *argo*

ultimately show *?thesis* **using** *add-carry-True-inc-nat True* **by** *simp*

next

case *False*

then show *?thesis* **using** *add-carry-True-inc-nat*[of xs ys] **by** *auto*

qed

lemma *add-carry-inc-nat-simps*:

```

add-carry True xs ys = inc-nat (add-carry False xs ys)
add-carry False (inc-nat xs) ys = inc-nat (add-carry False xs ys)
add-carry False xs (inc-nat ys) = inc-nat (add-carry False xs ys)
using inc-nat-add-carry[of - xs ys] add-carry-True-inc-nat[of xs ys]
by argo+

```

lemma *add-carry-assoc*: $\text{add-carry } c2 \text{ (add-carry } c1 \text{ xs ys) zs} = \text{add-carry } c1 \text{ xs (add-carry } c2 \text{ ys zs)}$

apply (*intro nat-lsbf-eqI*)

subgoal by (*simp add: add-carry-correct*)

subgoal

proof –

let *?t1* = *of-bool c1 + to-nat xs + to-nat ys*

let *?t2* = *of-bool c2 + to-nat ys + to-nat zs*

let *?t3* = *of-bool c1 + of-bool c2 + to-nat xs + to-nat ys + to-nat zs*

have $\text{length (add-carry } c2 \text{ (add-carry } c1 \text{ xs ys) zs)} = \text{max (max (max (max$

$(\text{length } xs) (\text{length } ys) (\text{floorlog } 2 \ ?t1) (\text{length } zs)$
 $(\text{floorlog } 2 \ ?t3)$
unfolding *length-add-carry add-carry-correct eval-bool-is-of-bool*
by (*intro arg-cong2[where f = max] refl arg-cong2[where f = floorlog]*) *simp*
also have ... = $\max (\max (\max (\max (\text{floorlog } 2 \ ?t1) (\text{floorlog } 2 \ ?t3)) (\text{length } xs)) (\text{length } ys)) (\text{length } zs)$
using *max commute max.assoc* **by** *presburger*
also have ... = $\max (\max (\max (\text{floorlog } 2 \ ?t3) (\text{length } xs)) (\text{length } ys)) (\text{length } zs)$ (*is ... = ?t4*)
by (*intro arg-cong2[where f = max] refl max.absorb2 floorlog-mono*) *simp*
finally have 1: $\text{length } (\text{add-carry } c2 (\text{add-carry } c1 \ xs \ ys) \ zs) = ?t4$.

have $\text{length } (\text{add-carry } c1 \ xs (\text{add-carry } c2 \ ys \ zs)) = \max (\max (\text{length } xs) (\max (\max (\text{length } ys) (\text{length } zs)) (\text{floorlog } 2 \ ?t2))) (\text{floorlog } 2 \ ?t3)$
unfolding *length-add-carry add-carry-correct eval-bool-is-of-bool*
by (*intro arg-cong2[where f = max] refl arg-cong2[where f = floorlog]*) *simp*
also have ... = $\max (\max (\max (\max (\text{floorlog } 2 \ ?t2) (\text{floorlog } 2 \ ?t3)) (\text{length } xs)) (\text{length } ys)) (\text{length } zs)$
using *max commute max.assoc* **by** *presburger*
also have ... = $\max (\max (\max (\text{floorlog } 2 \ ?t3) (\text{length } xs)) (\text{length } ys)) (\text{length } zs)$
by (*intro arg-cong2[where f = max] refl max.absorb2 floorlog-mono*) *simp*
finally have 2: $\text{length } (\text{add-carry } c1 \ xs (\text{add-carry } c2 \ ys \ zs)) = ?t4$.

show *?thesis* **unfolding** 1 2 **by** (*rule refl*)
qed
done

lemma *truncated-add-carry*:

assumes *truncated xs truncated ys*
shows *truncated (add-carry c xs ys)*
proof –
have $\text{length } (\text{add-carry } c \ xs \ ys) = \max (\max (\text{length } xs) (\text{length } ys)) (\text{bitsize } (\text{of-bool } c + \text{to-nat } xs + \text{to-nat } ys))$
unfolding *length-add-carry bitsize-is-floorlog* **by** *argo*
also have ... = $\max (\max (\text{bitsize } (\text{to-nat } xs)) (\text{bitsize } (\text{to-nat } ys))) (\text{bitsize } (\text{of-bool } c + \text{to-nat } xs + \text{to-nat } ys))$
using *truncated-iff' assms* **by** *algebra*
also have ... = $\text{bitsize } (\text{of-bool } c + \text{to-nat } xs + \text{to-nat } ys)$
using *bitsize-mono* **by** *simp*
also have ... = $\text{bitsize } (\text{to-nat } (\text{add-carry } c \ xs \ ys))$
by (*simp add: add-carry-correct*)
finally show *?thesis* **unfolding** *truncated-iff'* .
qed

8.7.3 Addition

definition *add-nat* :: *nat-lsbf* \Rightarrow *nat-lsbf* \Rightarrow *nat-lsbf* **where**

add-nat $x y = \text{add-carry } \text{False } x y$

corollary *length-add-nat-lower*: $\text{length } (\text{add-nat } xs \ ys) \geq \max (\text{length } xs) (\text{length } ys)$

unfolding *add-nat-def* **by** (*simp only: length-add-carry-lower*)

corollary *length-add-nat-upper*: $\text{length } (\text{add-nat } xs \ ys) \leq \max (\text{length } xs) (\text{length } ys) + 1$

unfolding *add-nat-def* **using** *length-add-carry-upper*[*of False xs ys*] **by** *simp*

corollary *add-nat-last-bit-True*: $\text{length } (\text{add-nat } xs \ ys) = \max (\text{length } xs) (\text{length } ys) + 1 \implies \exists zs. \text{add-nat } xs \ ys = zs \text{ @ } [\text{True}]$

unfolding *add-nat-def* **by** (*simp add: add-carry-last-bit-True*)

lemma *add-nat-correct*: $\text{to-nat } (\text{add-nat } x \ y) = \text{to-nat } x + \text{to-nat } y$

unfolding *add-nat-def* **using** *add-carry-correct* **by** *simp*

corollary *add-nat-com*: $\text{add-nat } xs \ ys = \text{add-nat } ys \ xs$

unfolding *add-nat-def* **by** (*simp add: add-carry-com*)

corollary *add-nat-assoc*: $\text{add-nat } xs \ (\text{add-nat } ys \ zs) = \text{add-nat } (\text{add-nat } xs \ ys) \ zs$

unfolding *add-nat-def* **using** *add-carry-assoc* **by** *simp*

corollary *truncated-add-nat*:

assumes *truncated xs truncated ys*

shows *truncated (add-nat xs ys)*

unfolding *add-nat-def*

by (*intro truncated-add-carry assms*)

8.8 Comparison and subtraction

8.8.1 Comparison

fun *compare-nat-same-length-reversed* :: *bool list* \Rightarrow *bool list* \Rightarrow *bool* **where**

compare-nat-same-length-reversed [] [] = *True*

| *compare-nat-same-length-reversed* (*False#xs*) (*False#ys*) = *compare-nat-same-length-reversed xs ys*

| *compare-nat-same-length-reversed* (*True#xs*) (*False#ys*) = *False*

| *compare-nat-same-length-reversed* (*False#xs*) (*True#ys*) = *True*

| *compare-nat-same-length-reversed* (*True#xs*) (*True#ys*) = *compare-nat-same-length-reversed xs ys*

| *compare-nat-same-length-reversed* - - = *undefined*

lemma *compare-nat-same-length-reversed-correct*:

$\text{length } xs = \text{length } ys \implies \text{compare-nat-same-length-reversed } xs \ ys \iff \text{to-nat } (\text{rev } xs) \leq \text{to-nat } (\text{rev } ys)$

proof (*induction xs ys rule: compare-nat-same-length-reversed.induct*)

case 1

then show *?case* **by** *simp*

next

```

    case (2 xs ys)
      have to-nat (rev (False # xs)) = to-nat (rev xs) to-nat (rev (False # ys)) =
to-nat (rev ys)
        using to-nat-app by simp-all
      then have to-nat (rev (False # xs)) ≤ to-nat (rev (False # ys))  $\longleftrightarrow$  to-nat (rev
xs) ≤ to-nat (rev ys)
        by simp
      then show ?case using 2 by simp
next
    case (3 xs ys)
      have to-nat (rev (True # xs)) = 2 ^ (length xs) + to-nat (rev xs)
        using to-nat-app by simp
      also have ... > to-nat (rev ys)
        using 3 to-nat-length-upper-bound[of rev ys] leI le-add-diff-inverse2 by fastforce
      also have to-nat (rev ys) = to-nat (rev (False # ys))
        using to-nat-app by simp
      finally have to-nat (rev (True # xs)) > to-nat (rev (False # ys)) .
      thus ?case using 3 by simp
next
    case (4 xs ys)
      have to-nat (rev (False # xs)) = to-nat (rev xs)
        using to-nat-app by simp
      also have ... ≤ 2 ^ (length xs)
        using to-nat-length-upper-bound[of rev xs] by simp
      also have ... ≤ to-nat (rev (True # ys))
        using to-nat-app 4 by simp
      finally have to-nat (rev (False # xs)) ≤ to-nat (rev (True # ys)) .
      thus ?case using 4 by simp
next
    case (5 xs ys)
      have to-nat (rev (True # xs)) = 2 ^ (length xs) + to-nat (rev xs) to-nat (rev
(True # ys)) = 2 ^ (length ys) + to-nat (rev ys)
        using to-nat-app by simp-all
      then have to-nat (rev (True # xs)) ≤ to-nat (rev (True # ys))  $\longleftrightarrow$  to-nat (rev
xs) ≤ to-nat (rev ys)
        using 5 by simp
      then show ?case using 5 by simp
next
    case (6-1 va)
      then show ?case by simp
next
    case (6-2 v va)
      then show ?case by simp
next
    case (6-3 v va)
      then show ?case by simp
next
    case (6-4 va)
      then show ?case by simp

```

qed

fun *compare-nat-same-length* :: *nat-lsbf* \Rightarrow *nat-lsbf* \Rightarrow *bool* **where**
compare-nat-same-length *xs* *ys* = *compare-nat-same-length-reversed* (*rev xs*) (*rev*
ys)

lemma *compare-nat-same-length-correct*:
length xs = *length ys* \implies *compare-nat-same-length* *xs* *ys* = (*to-nat xs* \leq *to-nat*
ys)
using *compare-nat-same-length-reversed-correct* **by** *simp*

definition *make-same-length* :: *nat-lsbf* \Rightarrow *nat-lsbf* \Rightarrow *nat-lsbf* \times *nat-lsbf* **where**
make-same-length *xs* *ys* = (*let* *n* = *max* (*length xs*) (*length ys*) *in* ((*fill n xs*), (*fill*
n ys)))

lemma *make-same-length-correct*:
assumes (*fill-xs*, *fill-ys*) = *make-same-length* *xs* *ys*
shows *length fill-ys* = *length fill-xs*
length fill-xs = *max* (*length xs*) (*length ys*)
to-nat fill-xs = *to-nat xs*
to-nat fill-ys = *to-nat ys*
using *assms* **by** (*simp-all add: Let-def make-same-length-def*)

definition *compare-nat* :: *nat-lsbf* \Rightarrow *nat-lsbf* \Rightarrow *bool* **where**
compare-nat *xs* *ys* = (*let* (*fill-xs*, *fill-ys*) = *make-same-length* *xs* *ys* *in* *compare-nat-same-length*
fill-xs *fill-ys*)

lemma *compare-nat-correct*: *compare-nat* *xs* *ys* = (*to-nat xs* \leq *to-nat ys*)
proof –
obtain *fill-xs* *fill-ys* **where** *fills-def*: *make-same-length* *xs* *ys* = (*fill-xs*, *fill-ys*)
by *fastforce*
then show *?thesis* **unfolding** *compare-nat-def* *Let-def*
using *make-same-length-correct*[*OF* *fills-def*[*symmetric*]]
using *compare-nat-same-length-reversed-correct*[*of* *rev fill-xs* *rev fill-ys*]
by *simp*
qed

8.8.2 Subtraction

definition *subtract-nat* :: *nat-lsbf* \Rightarrow *nat-lsbf* \Rightarrow *nat-lsbf* **where**
subtract-nat *xs* *ys* = (*if* *compare-nat* *xs* *ys* *then* [] *else*
let (*fill-xs*, *fill-ys*) = *make-same-length* *xs* *ys* *in*
butlast (*add-carry* *True* *fill-xs* (*map* *Not* *fill-ys*)))

lemma *add-complement*: *add-nat* *xs* (*map* *Not* *xs*) = *replicate* (*length xs*) *True*
proof (*induction xs*)
case *Nil*
then show *?case* **unfolding** *add-nat-def* **by** *simp*
next

case (*Cons a xs*)
have $\text{add-nat } (a \# xs) (\text{map Not } (a \# xs)) = \text{True} \# (\text{add-carry False } xs (\text{map Not } xs))$
unfolding *add-nat-def* **by** (*cases a*) *simp-all*
also have $\dots = \text{True} \# (\text{replicate } (\text{length } xs) \text{ True})$
using *Cons.IH* **by** (*simp add: add-nat-def*)
finally show *?case* **by** *simp*
qed

lemma *to-nat-complement*: $\text{to-nat } (\text{map Not } xs) = 2^{\wedge} (\text{length } xs) - 1 - \text{to-nat } xs$
using *add-complement[of xs]* *to-nat-replicate-true[of length xs]* *add-nat-correct[of xs map Not xs]*
by *simp*

lemma *to-nat-butlast*: $zs = xs @ [\text{True}] \implies \text{to-nat } (\text{butlast } zs) = \text{to-nat } zs - 2^{\wedge} \text{length } xs$
using *to-nat-app[of xs [True]]* **by** *simp*

lemma *inc-nat-true-prefix[simp]*: $\text{inc-nat } (\text{replicate } n \text{ True} @ [\text{False}] @ ys) = \text{replicate } n \text{ False} @ [\text{True}] @ ys$
by (*induction n arbitrary: ys*) *simp-all*

lemma *length-inc-nat-aux*: $zs = \text{replicate } n \text{ True} @ [\text{False}] @ ys \implies \text{length } (\text{inc-nat } zs) = \text{length } zs$
using *inc-nat-true-prefix[of n ys]* **by** *simp*

lemma *length-inc-nat-aux-2*: $\text{length } (\text{inc-nat } (xs @ [\text{False}] @ ys)) = \text{length } (xs @ [\text{False}] @ ys)$

proof –

define *zs* **where** $zs = xs @ [\text{False}] @ ys$
with *bit-strong-decomp-1* *[of zs False]* **obtain** *ys' n* **where** $zs = \text{replicate } n \text{ True} @ [\text{False}] @ ys'$
by *auto*

then show *?thesis* **using** *length-inc-nat-aux zs-def* **by** *simp*

qed

lemma *subtract-nat-aux*: $\text{to-nat } (\text{subtract-nat } xs \ ys) = (\text{to-nat } xs) - (\text{to-nat } ys) \wedge \text{length } (\text{subtract-nat } xs \ ys) \leq \max (\text{length } xs) (\text{length } ys)$

proof (*cases compare-nat xs ys*)

case *True*

then show *?thesis* **using** *compare-nat-correct* **unfolding** *subtract-nat-def* **by** *simp*

next

case *False*

obtain *fill-xs fill-ys* **where** *fills-def*: $\text{make-same-length } xs \ ys = (\text{fill-}xs, \text{fill-}ys)$

by *fastforce*

note *fills-props* = *make-same-length-correct[OF fills-def[symmetric]]*

```

define  $n$  where  $n = \max (\text{length } xs) (\text{length } ys)$ 
then have  $\text{length } \text{fill-}xs = n$   $\text{length } \text{fill-}ys = n$  using  $\text{fills-props}$  by  $\text{auto}$ 

from  $\text{False}$  have  $\text{to-nat } \text{fill-}xs > \text{to-nat } \text{fill-}ys$ 
using  $\text{fills-props}$   $\text{compare-nat-correct}$  by  $\text{simp}$ 
then have  $n > 0$  using  $\langle \text{length } \text{fill-}xs = n \rangle$  by  $\text{auto}$ 

let  $?add = \text{add-carry } \text{True } \text{fill-}xs (\text{map } \text{Not } \text{fill-}ys)$ 

have  $\text{subtract-nat-}xs\text{-}ys: \text{subtract-nat } xs\ ys = \text{butlast } ?add$ 
unfolding  $\text{subtract-nat-def}$  using  $\text{False } \text{fills-def}$  by  $\text{simp}$ 

have  $\text{to-nat } \text{fill-}ys \leq 2^n - 1$   $\text{to-nat } \text{fill-}xs \leq 2^n - 1$   $\text{to-nat } (\text{map } \text{Not } \text{fill-}ys)$ 
 $\leq 2^n - 1$ 
subgoal using  $\text{to-nat-length-upper-bound}$  $[\text{of } \text{fill-}ys]$   $\langle \text{length } \text{fill-}ys = n \rangle$  by  $\text{argo}$ 
subgoal using  $\text{to-nat-length-upper-bound}$  $[\text{of } \text{fill-}xs]$   $\langle \text{length } \text{fill-}xs = n \rangle$  by  $\text{argo}$ 
subgoal using  $\text{to-nat-length-upper-bound}$  $[\text{of } \text{map } \text{Not } \text{fill-}ys]$   $\langle \text{length } \text{fill-}ys =$ 
 $n \rangle$  by  $\text{simp}$ 
done
then have  $\text{to-nat } ?add \leq (2^n - 1) + (2^n - 1) + 1$  unfolding  $\text{add-carry-correct}$ 
by  $\text{simp}$ 
also have  $\dots = 2^{(n+1)} - 2 + 1$  by  $\text{simp}$ 
also have  $\dots = 2^{(n+1)} - 1$ 
using  $\text{Nat.diff-diff-right}$  $[\text{of } 1\ 2\ 2^{(n+1)}]$   $\text{Nat.diff-add-assoc2}$  $[\text{of } 2\ 2^{(n+1)}\ 1]$ 
by  $\text{simp}$ 
finally have  $\text{to-nat } ?add \leq \dots$  .

from  $\langle \text{to-nat } \text{fill-}xs > \text{to-nat } \text{fill-}ys \rangle$  have  $\text{to-nat } \text{fill-}xs \geq \text{to-nat } \text{fill-}ys + 1$  by
 $\text{simp}$ 
then have  $\text{to-nat } \text{fill-}xs + 2^n \geq 2^n + \text{to-nat } \text{fill-}ys + 1$  by  $\text{simp}$ 
then have  $\text{to-nat } \text{fill-}xs + (2^n - 1 - \text{to-nat } \text{fill-}ys) \geq 2^n$  by  $\text{simp}$ 
then have  $\text{to-nat } \text{fill-}xs + \text{to-nat } (\text{map } \text{Not } \text{fill-}ys) \geq 2^n$ 
using  $\text{to-nat-complement}$  $[\text{of } \text{fill-}ys]$   $\langle \text{length } \text{fill-}ys = n \rangle$  by  $\text{simp}$ 
then have  $\text{to-nat } ?add \geq 2^n$ 
using  $\text{add-carry-correct } \text{fills-props}$  by  $\text{simp}$ 
then have  $\text{length } ?add \geq n + 1$ 
using  $\text{to-nat-bound-to-length-bound}$  by  $\text{simp}$ 
then have  $\text{length } ?add = n + 1$ 
using  $\text{length-add-carry-upper}$  $[\text{of } \text{True } \text{fill-}xs\ \text{map } \text{Not } \text{fill-}ys]$   $\langle \text{length } \text{fill-}xs = n \rangle$ 
 $\langle \text{length } \text{fill-}ys = n \rangle$ 
by  $\text{simp}$ 

then obtain  $zs$  where  $?add = zs @ [\text{True}]$   $\text{length } zs = n$ 
using  $\text{add-carry-last-bit-True}$  $[\text{of } \text{True } \text{fill-}xs\ \text{map } \text{Not } \text{fill-}ys]$   $\langle \text{length } \text{fill-}xs = n \rangle$ 
 $\langle \text{length } \text{fill-}ys = n \rangle$ 
by  $\text{auto}$ 
then have  $1: \text{to-nat } (\text{butlast } ?add) = \text{to-nat } \text{fill-}xs + \text{to-nat } (\text{map } \text{Not } \text{fill-}ys) +$ 
 $1 - 2^n$ 

```


unfolding *to-nat-butlast*[*OF* $\langle ?add = zs @ [True] \rangle$]
using *add-carry-correct* **by** (*metis Suc-eq-plus1 add.assoc eval-bool.simps(1) plus-1-eq-Suc*)
also have $\dots = to-nat\ fill-x\ s + (2^n - 1 - to-nat\ fill-y\ s) + 1 - 2^n$
unfolding *to-nat-complement*[*of fill-ys*] $\langle length\ fill-ys = n \rangle$ **by** (*rule refl*)
also have $\dots = to-nat\ fill-x\ s + (2^n - 1) - to-nat\ fill-y\ s + 1 - 2^n$
using *le-add-diff-inverse*[*OF* $\langle to-nat\ fill-ys \leq 2^n - 1 \rangle$] **by** *linarith*
also have $\dots = to-nat\ fill-x\ s - to-nat\ fill-y\ s + (2^n - 1) - (2^n - 1)$
using $\langle to-nat\ fill-x\ s > to-nat\ fill-y\ s \rangle$ **by** *simp*
also have $\dots = to-nat\ fill-x\ s - to-nat\ fill-y\ s$ **by** *simp*
finally have $2: to-nat\ (subtract-nat\ x\ s\ y\ s) = to-nat\ x\ s - to-nat\ y\ s$
unfolding *subtract-nat-x-s-y\ s\ fills-props* .

have $3: length\ (butlast\ ?add) = n$
using $\langle length\ ?add = n + 1 \rangle$ **by** *simp*

show *?thesis*
apply (*intro conjI*)
subgoal by (*fact 2*)
subgoal using 3 **unfolding** *subtract-nat-x-s-y\ n-def[symmetric]* **by** *simp*
done

qed

corollary *subtract-nat-correct*: $to-nat\ (subtract-nat\ x\ s\ y\ s) = (to-nat\ x\ s) - (to-nat\ y\ s)$
using *subtract-nat-aux* **by** *simp*

corollary *length-subtract-nat-le*: $length\ (subtract-nat\ x\ s\ y\ s) \leq max\ (length\ x\ s)\ (length\ y\ s)$
using *subtract-nat-aux* **by** *simp*

8.9 (Grid) Multiplication

fun *grid-mul-nat* :: *nat-lsbf* \Rightarrow *nat-lsbf* \Rightarrow *nat-lsbf* **where**
grid-mul-nat [] - = []
| *grid-mul-nat* (*False#xs*) *y* = *False* # (*grid-mul-nat* *xs* *y*)
| *grid-mul-nat* (*True#xs*) *y* = *add-nat* (*False* # (*grid-mul-nat* *xs* *y*)) *y*

lemma *grid-mul-nat-correct*: $to-nat\ (grid-mul-nat\ x\ y) = to-nat\ x * to-nat\ y$
by (*induction x y rule: grid-mul-nat.induct*) (*simp-all add: add-nat-correct*)

lemma *length-grid-mul-nat*: $length\ (grid-mul-nat\ x\ s\ y\ s) \leq length\ x\ s + length\ y\ s$

proof (*induction xs ys rule: grid-mul-nat.induct*)

case ($1\ uu$)
then show *?case* **by** *simp*

next

case ($2\ x\ s\ y$)
then show *?case* **by** *simp*

next

```

case (3 xs y)
show ?case
proof (rule ccontr)
  assume  $\neg$  length (grid-mul-nat (True # xs) y)  $\leq$  length (True # xs) + length
y
  then have l: length (grid-mul-nat (True # xs) y) = length xs + length y + 2
  using length-add-nat-upper[of False # grid-mul-nat xs y] 3 by simp

  then have length (add-nat (False # grid-mul-nat xs y) y) = max (length (False
# grid-mul-nat xs y)) (length y) + 1
  using length-add-nat-upper[of False # grid-mul-nat xs y] 3 by simp
  then obtain as where add-nat (False # grid-mul-nat xs y) y = as @ [True]
  using add-nat-last-bit-True[of False # grid-mul-nat xs y] by auto
  then have as-def: grid-mul-nat (True # xs) y = as @ [True] by simp
  then have length-as: length as = length xs + length y + 1 using l by simp

  from as-def have m: to-nat (True # xs) * to-nat y = to-nat (as @ [True])
  using grid-mul-nat-correct by metis
  also have to-nat (as @ [True])  $\geq$  2 ^ length as
  using to-nat-length-lower-bound by simp
  also have 2 ^ length as = 2 ^ (length xs + length y + 1) using length-as by
simp
  also have to-nat (True # xs) * to-nat y < 2 ^ (length xs + 1) * 2 ^ length y
  apply (intro mult-less-le-imp-less)
  subgoal using to-nat-length-upper-bound[of True # xs] by simp
  subgoal using to-nat-length-upper-bound[of y] by simp
  subgoal by simp
  subgoal
    apply (rule ccontr)
    using m to-nat-length-lower-bound[of as] by simp
  done
  finally show False by (simp add: power-add)
qed
qed

```

8.10 Syntax bundles

abbreviation *shift-right-flip* xs n \equiv *shift-right* n xs

bundle *nat-lsbf-syntax*

begin

```

notation add-nat (infixl +n 65)
notation compare-nat (infixl  $\leq$ n 50)
notation subtract-nat (infixl -n 65)
notation grid-mul-nat (infixl *n 70)
notation shift-right-flip (infixl >>n 55)

```

end

bundle *no-nat-lsbf-syntax*

begin

```

no-notation add-nat (infixl  $+_n$  65)
no-notation compare-nat (infixl  $\leq_n$  50)
no-notation subtract-nat (infixl  $-_n$  65)
no-notation grid-mul-nat (infixl  $*_n$  70)
no-notation shift-right-flip (infixl  $>>_n$  55)
end

unbundle nat-lsb-syntax

end
theory Karatsuba-Runtime-Lemmas
  imports Complex-Main Akra-Bazzi.Akra-Bazzi-Method
begin

An explicit bound for a specific class of recursive functions.

context
  fixes a b c d :: nat
  fixes f :: nat  $\Rightarrow$  nat
  assumes small-bounds:  $f\ 0 \leq a$   $f\ (Suc\ 0) \leq a$ 
  assumes recursive-bound:  $\bigwedge n. n > 1 \implies f\ n \leq c * n + d + f\ (n\ div\ 2)$ 
begin

private fun g where
  g 0 = a
  | g (Suc 0) = a
  | g n =  $c * n + d + g\ (n\ div\ 2)$ 

private lemma f-g-bound:  $f\ n \leq g\ n$ 
  apply (induction n rule: g.induct)
  subgoal using small-bounds by simp
  subgoal using small-bounds by simp
  subgoal for x using recursive-bound[of Suc (Suc x)] by auto
  done

private lemma g-mono-aux:  $a \leq g\ n$ 
  by (induction n rule: g.induct) simp-all

private lemma g-mono:  $m \leq n \implies g\ m \leq g\ n$ 
proof (induction m arbitrary: n rule: g.induct)
  case 1
  then show ?case using g-mono-aux by simp
next
  case 2
  then show ?case using g-mono-aux by simp
next
  case ( $\exists x$ )
  then obtain y where  $n = Suc\ (Suc\ y)$  using Suc-le-D by blast
  have  $g\ (Suc\ (Suc\ x)) = c * Suc\ (Suc\ x) + d + g\ (Suc\ (Suc\ x)\ div\ 2)$ 
  by simp

```

also have $\dots \leq c * n + d + g (n \text{ div } 2)$
using \mathcal{P}
by (*metis add-mono add-mono-thms-linordered-semiring*(\mathcal{P}) *div-le-mono nat-mult-le-cancel-disj*)
finally show $?case$ **using** $\langle n = \text{Suc } (\text{Suc } y) \rangle$ **by** *simp*
qed

private lemma *g-powers-of-2*: $g (2 \wedge n) = d * n + c * (2 \wedge (n + 1) - 2) + a$
proof (*induction n*)
case (*Suc n*)
then obtain n' **where** $2 \wedge \text{Suc } n = \text{Suc } (\text{Suc } n')$
by (*metis g.cases less-exp not-less-eq zero-less-Suc*)
then have $g (2 \wedge \text{Suc } n) = c * 2 \wedge \text{Suc } n + d + g (2 \wedge n)$
by (*metis g.simps*(\mathcal{P}) *nonzero-mult-div-cancel-right power-Suc2 zero-neq-numeral*)
also have $\dots = c * 2 \wedge \text{Suc } n + d + d * n + c * (2 \wedge (n + 1) - 2) + a$
using *Suc* **by** *simp*
also have $\dots = d * \text{Suc } n + c * (2 \wedge \text{Suc } n + (2 \wedge (n + 1) - 2)) + a$
using *add-mult-distrib2*[*symmetric, of c*] **by** *simp*
finally show $?case$ **by** *simp*
qed *simp*

private lemma *pow-ineq*:
assumes $m \geq (1 :: \text{nat})$
assumes $p \geq 2$
shows $p \wedge m > m$
using *assms*
apply (*induction m*)
subgoal by *simp*
subgoal for m
by (*cases m*) (*simp-all add: less-trans-Suc*)
done

private lemma *next-power-of-2*:
assumes $m \geq (1 :: \text{nat})$
shows $\exists n k. m = 2 \wedge n + k \wedge k < 2 \wedge n$
proof –
from *ex-power-ivl1*[*OF order.refl assms*] **obtain** n **where** $2 \wedge n \leq m < 2 \wedge (n + 1)$
by *auto*
then have $m = 2 \wedge n + (m - 2 \wedge n)$ $m - 2 \wedge n < 2 \wedge n$ **by** *simp-all*
then show $?thesis$ **by** *blast*
qed

lemma *div-2-recursion-linear*: $f n \leq (2 * d + 4 * c) * n + a$
proof (*cases n* ≥ 1)
case *True*
then obtain $m k$ **where** $n = 2 \wedge m + k$ $k < 2 \wedge m$ **using** *next-power-of-2* **by** *blast*
have $f n \leq g n$ **using** *f-g-bound* **by** *simp*
also have $\dots \leq g (2 \wedge m + 2 \wedge m)$ **using** $\langle n = 2 \wedge m + k \rangle$ $\langle k < 2 \wedge m \rangle$ *g-mono*

```

by simp
  also have ... = d * Suc m + c * (2 ^ (Suc m + 1) - 2) + a
    using g-powers-of-2[of Suc m]
    apply (subst mult-2[symmetric])
    apply (subst power-Suc[symmetric])
    .
  also have ... ≤ d * Suc m + c * 2 ^ (Suc m + 1) + a by simp
  also have ... ≤ d * 2 ^ Suc m + c * 2 ^ (Suc m + 1) + a using less-exp[of Suc
m]
    by (meson add-le-mono less-or-eq-imp-le mult-le-mono)
  also have ... = (2 * d + 4 * c) * 2 ^ m + a using mult.assoc add-mult-distrib
by simp
  also have ... ≤ (2 * d + 4 * c) * n + a
    using ⟨n = 2 ^ m + k⟩ power-increasing[of m n] by simp
  finally show ?thesis .
next
  case False
  then have n = 0 by simp
  then show ?thesis using small-bounds by simp
qed

end

```

General Lemmas for Landau notation.

lemma *landau-o-plus-aux'*:

```

fixes f g
assumes f ∈ o[F](g)
shows O[F](g) = O[F](λx. f x + g x)
apply (intro equalityI subsetI)
subgoal using landau-o.big.trans[OF - landau-o.plus-aux[OF assms]] by simp
subgoal for h
  using assms by simp
done

```

lemma *powr-bigo-linear-index-transformation*:

```

fixes fl :: nat ⇒ nat
fixes f :: nat ⇒ real
assumes (λx. real (fl x)) ∈ O(λn. real n)
assumes f ∈ O(λn. real n powr p)
assumes p > 0
shows f ∘ fl ∈ O(λn. real n powr p)

```

proof –

```

obtain c1 where c1 > 0 ∀F x in sequentially. norm (real (fl x)) ≤ c1 * norm
(real x)
  using landau-o.bigE[OF assms(1)] by auto
then obtain N1 where fl-bound: ∀x. x ≥ N1 ⟶ norm (real (fl x)) ≤ c1 *
norm (real x)
  unfolding eventually-at-top-linorder by blast
obtain c2 where c2 > 0 ∀F x in sequentially. norm (f x) ≤ c2 * norm (real x)

```

```

powr p)
  using landau-o.bigE[OF assms(2)] by auto
  then obtain N2 where f-bound:  $\forall x. x \geq N2 \longrightarrow \text{norm } (f x) \leq c2 * \text{norm } (\text{real } x \text{ powr } p)$ 
  unfolding eventually-at-top-linorder by blast

  define cf :: real where cf = Max {norm (f y) | y. y ≤ N2}
  then have cf ≥ 0 using Max-in[of {norm (f y) | y. y ≤ N2}] norm-ge-zero by
fastforce
  define c where c = c2 * c1 powr p
  then have c > 0 using ⟨c1 > 0⟩ ⟨c2 > 0⟩ by simp

  have  $\forall x. x \geq N1 \longrightarrow \text{norm } (f (fl x)) \leq cf + c * \text{norm } (\text{real } x) \text{ powr } p$ 
  proof (intro allI impI)
    fix x
    assume x ≥ N1
    show norm (f (fl x)) ≤ cf + c * norm (real x) powr p
    proof (cases fl x ≥ N2)
      case True
        then have norm (f (fl x)) ≤ c2 * norm (real (fl x) powr p)
          using f-bound by simp
        also have ... = c2 * norm (real (fl x)) powr p
          by simp
        also have ... ≤ c2 * (c1 * norm (real x)) powr p
          apply (intro mult-mono order.refl powr-mono2 norm-ge-zero)
          subgoal using ⟨p > 0⟩ by simp
          subgoal using fl-bound ⟨x ≥ N1⟩ by simp
          subgoal using ⟨c2 > 0⟩ by simp
          subgoal by simp
        done
        also have ... = c2 * (c1 powr p * norm (real x) powr p)
          apply (intro arg-cong[where f = (*) c2] powr-mult norm-ge-zero)
          using ⟨c1 > 0⟩ by simp
        also have ... = c * norm (real x) powr p unfolding c-def by simp
        also have ... ≤ cf + c * norm (real x) powr p using ⟨cf ≥ 0⟩ by simp
        finally show ?thesis .
      case False
        then have norm (f (fl x)) ≤ cf unfolding cf-def
          by (intro Max-ge) auto
        also have ... ≤ cf + c * norm (real x) powr p
          using ⟨c > 0⟩ by simp
        finally show ?thesis .
    done
  qed
  then have f ∘ fl ∈ O( $\lambda x. cf + c * (\text{real } x) \text{ powr } p$ )
    apply (intro landau-o.big-mono)
    unfolding eventually-at-top-linorder comp-apply by fastforce
  also have ... = O( $\lambda x. c * (\text{real } x) \text{ powr } p$ )

```

proof (*intro landau-o-plus-aux'*[*symmetric*])
have $(\lambda x. cf) \in O(\lambda x. \text{real } x \text{ powr } 0)$ **by** *simp*
moreover have $(\lambda x. \text{real } x \text{ powr } 0) \in o(\lambda x. \text{real } x \text{ powr } p)$
using *iffD2[OF powr-smallo-iff, OF filterlim-real-sequentially-sequentially-bot*
 $\langle p > 0 \rangle]$.
ultimately have $(\lambda x. cf) \in o(\lambda x. \text{real } x \text{ powr } p)$
by (*rule landau-o.big-small-trans*)
also have $\dots = o(\lambda x. c * (\text{real } x) \text{ powr } p)$
using *landau-o.small.cmult* $\langle c > 0 \rangle$ **by** *simp*
finally show $(\lambda x. cf) \in \dots$.
qed
also have $\dots = O(\lambda x. (\text{real } x) \text{ powr } p)$ **using** *landau-o.big.cmult* $\langle c > 0 \rangle$ **by** *simp*
finally show *?thesis* .
qed

lemma *real-mono*: $(a \leq b) = (\text{real } a \leq \text{real } b)$
by *simp*

lemma *real-linear*: $\text{real } (a + b) = \text{real } a + \text{real } b$
by *simp*

lemma *real-multiplicative*: $\text{real } (a * b) = \text{real } a * \text{real } b$
by *simp*

lemma (*in landau-pair*) *big-1-mult-left*:
fixes $f g h$
assumes $f \in L F (g) \ h \in L F (\lambda \cdot. 1)$
shows $(\lambda x. h x * f x) \in L F (g)$
proof –
have $(\lambda x. f x * h x) \in L F (g)$ **using** *assms* **by** (*rule big-1-mult*)
also have $(\lambda x. f x * h x) = (\lambda x. h x * f x)$ **by** *auto*
finally show *?thesis* .
qed

lemma *norm-nonneg*: $x \geq 0 \implies \text{norm } x = x$ **by** *simp*

lemma *landau-mono-always*:
fixes $f g$
assumes $\bigwedge x. f x \geq (0 :: \text{real}) \ \bigwedge x. g x \geq 0$
assumes $\bigwedge x. f x \leq g x$
shows $f \in O[F](g)$
apply (*intro landau-o.bigI[of 1]*)
using *assms* **by** *simp-all*

end

9 Running time of *Nat-LSBF*

theory *Nat-LSBF-TM*

imports *Nat-LSBF ../Karatsuba-Runtime-Lemmas ../Main-TM ../Estimation-Method*
begin

9.1 Truncating and filling

fun *truncate-reversed-tm* :: *nat-lsbf* \Rightarrow *nat-lsbf tm* **where**
truncate-reversed-tm [] = 1 **return** []
| *truncate-reversed-tm* (*x # xs*) = 1 (if *x* then **return** (*x # xs*) else *truncate-reversed-tm xs*)

lemma *val-truncate-reversed-tm[simp, val-simp]*: *val (truncate-reversed-tm xs) = truncate-reversed xs*
by (*induction xs rule: truncate-reversed-tm.induct*) *simp-all*

lemma *time-truncate-reversed-tm-le*: *time (truncate-reversed-tm xs) \leq length xs + 1*
by (*induction xs rule: truncate-reversed-tm.induct*) *simp-all*

definition *truncate-tm* :: *nat-lsbf* \Rightarrow *nat-lsbf tm* **where**
truncate-tm xs = 1 do {
rev-xs \leftarrow *rev-tm xs*;
truncate-rev-xs \leftarrow *truncate-reversed-tm rev-xs*;
rev-tm truncate-rev-xs
}

lemma *val-truncate-tm[simp, val-simp]*: *val (truncate-tm xs) = truncate xs*
by (*simp add: truncate-tm-def Nat-LSBF.truncate-def*)

lemma *time-truncate-tm-le*: *time (truncate-tm xs) \leq 3 * length xs + 6*
using *add-mono[OF time-truncate-reversed-tm-le[of rev xs] truncate-reversed-length-ineq[of rev xs]]*
by (*simp add: truncate-tm-def*)

definition *fill-tm* :: *nat* \Rightarrow *nat-lsbf* \Rightarrow *nat-lsbf tm* **where**
fill-tm n xs = 1 do {
k \leftarrow *length-tm xs*;
l \leftarrow *n -_t k*;
zeros \leftarrow *replicate-tm l False*;
xs @_t zeros
}

lemma *val-fill-tm[simp, val-simp]*: *val (fill-tm n xs) = fill n xs*
by (*simp add: fill-tm-def fill-def*)

lemma *com-f-of-min-max*: *f a b = f b a \implies f (min a b) (max a b) = f a b*
by (*cases a \leq b; simp add: max-def min-def*)

lemma *add-min-max*: *min (a::'a:: ordered-ab-semigroup-add) b + max a b = a + b*
by (*intro com-f-of-min-max add.commute*)

lemma *time-fill-tm*: $\text{time } (\text{fill-tm } n \text{ } xs) = 2 * \text{length } xs + n + 5$
by (*simp add: fill-tm-def time-replicate-tm add-min-max*)

lemma *time-fill-tm-le*: $\text{time } (\text{fill-tm } n \text{ } xs) \leq 3 * \max n (\text{length } xs) + 5$
unfolding *time-fill-tm* **by** *simp*

9.2 Right-shifts

definition *shift-right-tm* :: $\text{nat} \Rightarrow \text{nat-lsbf} \Rightarrow \text{nat-lsbf } tm$ **where**
shift-right-tm $n \text{ } xs = 1$ **do** {
r \leftarrow *replicate-tm* $n \text{ } False$;
r @_t *xs*
}

lemma *val-shift-right-tm*[*simp, val-simp*]: $\text{val } (\text{shift-right-tm } n \text{ } xs) = xs \gg_n n$
by (*simp add: shift-right-tm-def shift-right-def*)

lemma *time-shift-right-tm*[*simp*]: $\text{time } (\text{shift-right-tm } n \text{ } xs) = 2 * n + 3$
by (*simp add: shift-right-tm-def time-replicate-tm*)

9.3 Subdividing lists

9.3.1 Splitting a list in two blocks

definition *split-at-tm* :: $\text{nat} \Rightarrow 'a \text{ list} \Rightarrow ('a \text{ list} \times 'a \text{ list}) \text{ } tm$ **where**
split-at-tm $k \text{ } xs = 1$ **do** {
xs1 \leftarrow *take-tm* $k \text{ } xs$;
xs2 \leftarrow *drop-tm* $k \text{ } xs$;
return (*xs1*, *xs2*)
}

lemma *val-split-at-tm*[*simp, val-simp*]: $\text{val } (\text{split-at-tm } k \text{ } xs) = \text{split-at } k \text{ } xs$
unfolding *split-at-tm-def* **by** *simp*

lemma *time-split-at-tm*: $\text{time } (\text{split-at-tm } k \text{ } xs) = 2 * \min k (\text{length } xs) + 3$
unfolding *split-at-tm-def tm-time-simps time-take-tm time-drop-tm* **by** *simp*

definition *split-tm* :: $\text{nat-lsbf} \Rightarrow (\text{nat-lsbf} \times \text{nat-lsbf}) \text{ } tm$ **where**
split-tm $xs = 1$ **do** {
n \leftarrow *length-tm* xs ;
n-div-2 \leftarrow $n \text{ div}_t 2$;
split-at-tm $n\text{-div-2 } xs$
}

lemma *val-split-tm*[*simp, val-simp*]: $\text{val } (\text{split-tm } xs) = \text{split } xs$
by (*simp add: split-tm-def split-def Let-def*)

lemma *time-split-tm-le*: $\text{time } (\text{split-tm } xs) \leq 10 * \text{length } xs + 16$
using *time-divide-nat-tm-le*[*of length xs 2*]

by (simp add: split-tm-def time-split-at-tm)

9.3.2 Splitting a list in multiple blocks

```

fun subdivide-tm :: nat  $\Rightarrow$  'a list  $\Rightarrow$  'a list list tm where
  subdivide-tm 0 xs =1 undefined
| subdivide-tm n [] =1 return []
| subdivide-tm n xs =1 do {
  r  $\leftarrow$  take-tm n xs;
  s  $\leftarrow$  drop-tm n xs;
  rs  $\leftarrow$  subdivide-tm n s;
  return (r # rs)
}

```

lemma val-subdivide-tm[simp, val-simp]: $n > 0 \implies \text{val } (\text{subdivide-tm } n \text{ xs}) = \text{subdivide } n \text{ xs}$

by (induction n xs rule: subdivide.induct) simp-all

lemma time-subdivide-tm-le-aux:

assumes $n > 0$

shows $\text{time } (\text{subdivide-tm } n \text{ xs}) \leq k * (2 * n + 3) + \text{time } (\text{subdivide-tm } n \text{ (drop } (k * n) \text{ xs)})$

proof (induction k arbitrary: xs)

case (Suc k)

show ?case

proof (cases xs)

case Nil

then show ?thesis by simp

next

case (Cons a l)

then have $\text{time } (\text{subdivide-tm } n \text{ (a # l)}) \leq 2 * n + 3 + \text{time } (\text{subdivide-tm } n \text{ (drop } n \text{ (a # l))})$

using gr0-implies-Suc[OF assms] by (auto simp: time-take-tm time-drop-tm)

also have $\dots \leq 2 * n + 3 + (k * (2 * n + 3) + \text{time } (\text{subdivide-tm } n \text{ (drop } (k * n) \text{ (drop } n \text{ (a # l))})))$

by (intro add-mono order.refl Suc)

also have $\dots = \text{Suc } k * (2 * n + 3) + \text{time } (\text{subdivide-tm } n \text{ (drop } (\text{Suc } k * n) \text{ (a # l))})$

by (simp add: add.commute)

finally show ?thesis using Cons by simp

qed

qed simp

lemma time-subdivide-tm-le:

fixes xs :: 'a list

assumes $n > 0$

shows $\text{time } (\text{subdivide-tm } n \text{ xs}) \leq 5 * \text{length } xs + 2 * n + 4$

proof –

define k where $k = \text{length } xs \text{ div } n + 1$

then have $k * n \geq \text{length } xs$ **using** *assms*
by (*meson div-less-iff-less-mult less-add-one order-less-imp-le*)
then have *drop-Nil*: $\text{drop } (k * n) \text{ } xs = []$ **by** *simp*
have $\text{time } (\text{subdivide-tm } n \text{ } xs) \leq k * (2 * n + 3) + \text{time } (\text{subdivide-tm } n \text{ } ([] :: 'a \text{ list}))$
using *time-subdivide-tm-le-aux*[*OF assms, of xs k*] **unfolding** *drop-Nil* .
also have $\dots = k * (2 * n + 3) + 1$ **using** *gr0-implies-Suc*[*OF assms*] **by** *auto*
also have $\dots = (2 * n * (\text{length } xs \text{ div } n) + 2 * n) + 3 * (\text{length } xs \text{ div } n) + 4$
unfolding *k-def* **by** (*simp add: add-mult-distrib2*)
also have $\dots \leq 5 * \text{length } xs + 2 * n + 4$
using *times-div-less-eq-dividend*[*of n length xs*] *div-le-dividend*[*of length xs n*]
by *linarith*
finally show *?thesis* .
qed

9.4 The *bitsize* function

fun *bitsize-tm* :: $\text{nat} \Rightarrow \text{nat tm}$ **where**
bitsize-tm 0 = 1 return 0
| *bitsize-tm n = 1* **do** {
 $n\text{-div-2} \leftarrow n \text{ div}_t 2$;
 $r \leftarrow \text{bitsize-tm } n\text{-div-2}$;
 $1 +_t r$
}

lemma *val-bitsize-tm*[*simp, val-simp*]: $\text{val } (\text{bitsize-tm } n) = \text{bitsize } n$
by (*induction n rule: bitsize-tm.induct*) *simp-all*

fun *time-bitsize-tm-bound* :: $\text{nat} \Rightarrow \text{nat}$ **where**
time-bitsize-tm-bound 0 = 1
| *time-bitsize-tm-bound n = 14 + 8 * n + time-bitsize-tm-bound (n div 2)*

lemma *time-bitsize-tm-aux*:
 $\text{time } (\text{bitsize-tm } n) \leq \text{time-bitsize-tm-bound } n$
apply (*induction n rule: bitsize-tm.induct*)
subgoal by *simp*
subgoal for n **using** *time-divide-nat-tm-le*[*of Suc n 2*] **by** *simp*
done

lemma *time-bitsize-tm-aux2*: $\text{time-bitsize-tm-bound } n \leq (2 * 8 + 4 * 14) * n + 23$
apply (*intro div-2-recursion-linear*)
using *less-iff-Suc-add* **by** *auto*

lemma *time-bitsize-tm-le*: $\text{time } (\text{bitsize-tm } n) \leq 72 * n + 23$
using *order.trans*[*OF time-bitsize-tm-aux time-bitsize-tm-aux2*] **by** *simp*

9.4.1 The *is-power-of-2* function

fun *is-power-of-2-tm* :: $\text{nat} \Rightarrow \text{bool tm}$ **where**

```

is-power-of-2-tm 0 =1 return False
| is-power-of-2-tm (Suc 0) =1 return True
| is-power-of-2-tm n =1 do {
  n-mod-2 ← n modt 2;
  n-div-2 ← n divt 2;
  c1 ← n-mod-2 =t 0;
  c2 ← is-power-of-2-tm n-div-2;
  c1 ∧t c2
}

```

lemma *val-is-power-of-2-tm*[simp, val-simp]: *val (is-power-of-2-tm n) = is-power-of-2 n*

by (*induction n rule: is-power-of-2-tm.induct*) *simp-all*

lemma *time-is-power-of-2-tm-le*: *time (is-power-of-2-tm n) ≤ 114 * n + 1*

proof –

have *time (is-power-of-2-tm n) ≤ (2 * 25 + 4 * 16) * n + 1*

apply (*intro div-2-recursion-linear*)

subgoal by *simp*

subgoal by *simp*

subgoal premises *prems for n*

proof –

from *prems obtain n' where n = Suc (Suc n')*

by (*metis Suc-diff-1 Suc-diff-Suc order-less-trans zero-less-one*)

then have *time (is-power-of-2-tm n) =*

time (n mod_t 2) +

time (n div_t 2) +

time (is-power-of-2-tm (n div 2)) + 3

by (*simp add: time-equal-nat-tm*)

also have *... ≤ 16 * n + time (is-power-of-2-tm (n div 2)) + 25*

apply (*estimation estimate: time-mod-nat-tm-le*)

apply (*estimation estimate: time-divide-nat-tm-le*)

apply *simp*

done

finally show *?thesis by simp*

qed

done

then show *?thesis by simp*

qed

definition *next-power-of-2-tm* :: *nat ⇒ nat tm where*

next-power-of-2-tm n =1 do {

b ← is-power-of-2-tm n;

if b then return n else do {

r ← bitsize-tm n;

2 ^t r

}

}

```

lemma val-next-power-of-2-tm[simp, val-simp]: val (next-power-of-2-tm n) = next-power-of-2
n
  by (simp add: next-power-of-2-tm-def)

lemma time-next-power-of-2-tm-le: time (next-power-of-2-tm n) ≤ 208 * n + 37
proof (cases is-power-of-2 n)
  case True
  then show ?thesis
    using time-is-power-of-2-tm-le[of n]
    by (simp add: next-power-of-2-tm-def)
next
  case False
  then have time (next-power-of-2-tm n) =
    time (is-power-of-2-tm n) +
    time (bitsize-tm n) +
    time (power-nat-tm 2 (bitsize n)) + 1
    by (simp add: next-power-of-2-tm-def)
  also have ... ≤ 186 * n + 6 * 2 ^ (bitsize n) + 5 * bitsize n + 26
    apply (estimation estimate: time-is-power-of-2-tm-le)
    apply (estimation estimate: time-bitsize-tm-le)
    apply (estimation estimate: time-power-nat-tm-le)
    by simp
  also have ... ≤ 186 * n + 11 * 2 ^ (bitsize n) + 26
    by simp
  also have ... ≤ 208 * n + 37
    by (estimation estimate: two-pow-bitsize-bound) simp
  finally show ?thesis .
qed

```

9.5 Addition

```

fun bit-add-carry-tm :: bool ⇒ bool ⇒ bool ⇒ (bool × bool) tm where
bit-add-carry-tm False False False = 1 return (False, False)
| bit-add-carry-tm False False True = 1 return (True, False)
| bit-add-carry-tm False True False = 1 return (True, False)
| bit-add-carry-tm False True True = 1 return (False, True)
| bit-add-carry-tm True False False = 1 return (True, False)
| bit-add-carry-tm True False True = 1 return (False, True)
| bit-add-carry-tm True True False = 1 return (False, True)
| bit-add-carry-tm True True True = 1 return (True, True)

```

```

lemma val-bit-add-carry-tm[simp, val-simp]: val (bit-add-carry-tm x y z) = bit-add-carry
x y z

```

```

by (induction x y z rule: bit-add-carry-tm.induct; simp)

```

```

lemma time-bit-add-carry-tm[simp]: time (bit-add-carry-tm x y z) = 1

```

```

by (induction x y z rule: bit-add-carry-tm.induct; simp)

```

```

fun inc-nat-tm :: nat-lsbf ⇒ nat-lsbf tm where

```

```

inc-nat-tm [] =1 return [True]
| inc-nat-tm (False # xs) =1 return (True # xs)
| inc-nat-tm (True # xs) =1 do {
  r ← inc-nat-tm xs;
  return (False # r)
}

```

lemma *val-inc-nat-tm*[simp, val-simp]: *val (inc-nat-tm xs) = inc-nat xs*
by (*induction xs rule: inc-nat-tm.induct*) *simp-all*

lemma *time-inc-nat-tm-le*: *time (inc-nat-tm xs) ≤ length xs + 1*
by (*induction xs rule: inc-nat-tm.induct*) *simp-all*

```

fun add-carry-tm :: bool ⇒ nat-lsbf ⇒ nat-lsbf ⇒ nat-lsbf tm where
add-carry-tm False [] y =1 return y
| add-carry-tm False (x # xs) [] =1 return (x # xs)
| add-carry-tm True [] y =1 do {
  r ← inc-nat-tm y;
  return r
}
| add-carry-tm True (x # xs) [] =1 do {
  r ← inc-nat-tm (x # xs);
  return r
}
| add-carry-tm c (x # xs) (y # ys) =1 do {
  (a, b) ← bit-add-carry-tm c x y;
  r ← add-carry-tm b xs ys;
  return (a # r)
}

```

lemma *val-add-carry-tm*[simp, val-simp]: *val (add-carry-tm c xs ys) = add-carry c xs ys*
by (*induction c xs ys rule: add-carry-tm.induct*) (*simp-all split: prod.splits*)

lemma *time-add-carry-tm-le*: *time (add-carry-tm c xs ys) ≤ 2 * max (length xs) (length ys) + 2*

proof (*induction c xs ys rule: add-carry-tm.induct*)

case (3 y)

then show ?*case* **using** *time-inc-nat-tm-le*[of y] **by** *simp*

next

case (4 x xs)

then show ?*case* **using** *time-inc-nat-tm-le*[of x # xs] **by** *simp*

qed (*simp-all split: prod.splits*)

```

definition add-nat-tm :: nat-lsbf ⇒ nat-lsbf ⇒ nat-lsbf tm where
add-nat-tm xs ys =1 do {
  r ← add-carry-tm False xs ys;
  return r
}

```

lemma *val-add-nat-tm*[*simp, val-simp*]: *val* (*add-nat-tm* *xs ys*) = *xs* +_{*n*} *ys*
by (*simp add: add-nat-tm-def add-nat-def*)

lemma *time-add-nat-tm-le*: *time* (*add-nat-tm* *xs ys*) ≤ 2 * *max* (*length* *xs*) (*length* *ys*) + 3
using *time-add-carry-tm-le*[*of - xs ys*] **by** (*simp add: add-nat-tm-def*)

9.6 Comparison and subtraction

fun *compare-nat-same-length-reversed-tm* :: *bool list* ⇒ *bool list* ⇒ *bool tm* **where**
compare-nat-same-length-reversed-tm [] [] = 1 *return True*
| *compare-nat-same-length-reversed-tm* (*False* # *xs*) (*False* # *ys*) = 1 *compare-nat-same-length-reversed-tm* *xs ys*
| *compare-nat-same-length-reversed-tm* (*True* # *xs*) (*False* # *ys*) = 1 *return False*
| *compare-nat-same-length-reversed-tm* (*False* # *xs*) (*True* # *ys*) = 1 *return True*
| *compare-nat-same-length-reversed-tm* (*True* # *xs*) (*True* # *ys*) = 1 *compare-nat-same-length-reversed-tm* *xs ys*
| *compare-nat-same-length-reversed-tm* - - = 1 *undefined*

lemma *val-compare-nat-same-length-reversed-tm*[*simp, val-simp*]:
assumes *length* *xs* = *length* *ys*
shows *val* (*compare-nat-same-length-reversed-tm* *xs ys*) = *compare-nat-same-length-reversed* *xs ys*
using *assms* **by** (*induction* *xs ys* *rule: compare-nat-same-length-reversed-tm.induct*)
simp-all

lemma *time-compare-nat-same-length-reversed-tm-le*:
length *xs* = *length* *ys* ⇒ *time* (*compare-nat-same-length-reversed-tm* *xs ys*) ≤ *length* *xs* + 1
by (*induction* *xs ys* *rule: compare-nat-same-length-reversed-tm.induct*) *simp-all*

fun *compare-nat-same-length-tm* :: *nat-lsbf* ⇒ *nat-lsbf* ⇒ *bool tm* **where**
compare-nat-same-length-tm *xs ys* = 1 *do* {
 rev-xs ← *rev-tm* *xs*;
 rev-ys ← *rev-tm* *ys*;
 compare-nat-same-length-reversed-tm *rev-xs rev-ys*
}

lemma *val-compare-nat-same-length-tm*[*simp, val-simp*]:
assumes *length* *xs* = *length* *ys*
shows *val* (*compare-nat-same-length-tm* *xs ys*) = *compare-nat-same-length* *xs ys*
using *assms* **by** *simp*

lemma *time-compare-nat-same-length-tm-le*:
length *xs* = *length* *ys* ⇒ *time* (*compare-nat-same-length-tm* *xs ys*) ≤ 3 * *length* *xs* + 6
using *time-compare-nat-same-length-reversed-tm-le*[*of rev xs rev ys*]
by *simp*

definition *make-same-length-tm* :: *nat-lsbf* \Rightarrow *nat-lsbf* \Rightarrow (*nat-lsbf* \times *nat-lsbf*) *tm*

where

```

make-same-length-tm xs ys =1 do {
  len-xs  $\leftarrow$  length-tm xs;
  len-ys  $\leftarrow$  length-tm ys;
  n  $\leftarrow$  max-nat-tm len-xs len-ys;
  fill-xs  $\leftarrow$  fill-tm n xs;
  fill-ys  $\leftarrow$  fill-tm n ys;
  return (fill-xs, fill-ys)
}

```

lemma *val-make-same-length-tm*[*simp*, *val-simp*]: *val* (*make-same-length-tm* *xs ys*)

= *make-same-length* *xs ys*

by (*simp* add: *make-same-length-tm-def* *make-same-length-def* del: *max-nat-tm.simps*)

lemma *time-make-same-length-tm-le*: *time* (*make-same-length-tm* *xs ys*) \leq 10 * *max* (*length xs*) (*length ys*) + 16

proof –

have *time* (*make-same-length-tm* *xs ys*) = 13 + 3 * *length xs* + 3 * *length ys* +
(*time* (*max-nat-tm* (*length xs*) (*length ys*)) + 2 * *max* (*length xs*) (*length ys*))

by (*simp* add: *make-same-length-tm-def* *time-fill-tm* del: *max-nat-tm.simps*)

also have ... \leq 10 * *max* (*length xs*) (*length ys*) + 16

using *time-max-nat-tm-le*[of *length xs length ys*] **by** *simp*

finally show ?*thesis* .

qed

definition *compare-nat-tm* :: *nat-lsbf* \Rightarrow *nat-lsbf* \Rightarrow *bool tm* **where**

```

compare-nat-tm xs ys =1 do {
  (fill-xs, fill-ys)  $\leftarrow$  make-same-length-tm xs ys;
  compare-nat-same-length-tm fill-xs fill-ys
}

```

lemma *val-compare-nat-tm*[*simp*, *val-simp*]: *val* (*compare-nat-tm* *xs ys*) = (*xs* \leq_n

ys)

using *make-same-length-correct*[**where** *xs* = *xs* **and** *ys* = *ys*]

by (*simp* add: *compare-nat-tm-def* *compare-nat-def* del: *compare-nat-same-length-tm.simps* *compare-nat-same-length.simps* *split*: *prod.splits*)

lemma *time-compare-nat-tm-le*: *time* (*compare-nat-tm* *xs ys*) \leq 13 * *max* (*length xs*) (*length ys*) + 23

proof –

obtain *fill-xs fill-ys* **where** *fills-defs*: *make-same-length* *xs ys* = (*fill-xs*, *fill-ys*)

by *fastforce*

then have *time* (*compare-nat-tm* *xs ys*) = *time* (*make-same-length-tm* *xs ys*) +
time (*compare-nat-same-length-tm* *fill-xs fill-ys*) + 1

by (*simp* add: *compare-nat-tm-def* del: *compare-nat-same-length-tm.simps*)

also have ... \leq (10 * *max* (*length xs*) (*length ys*) + 16) +

(3 * *max* (*length xs*) (*length ys*) + 6) + 1

apply (*intro add-mono order.refl time-make-same-length-tm-le*)
using *time-compare-nat-same-length-tm-le*[*of fill-xs fill-ys*]
using *make-same-length-correct*[*OF fills-defs*[*symmetric*]] **by** *argo*
finally show *?thesis* **by** *simp*
qed

definition *subtract-nat-tm* :: *nat-lsbf* \Rightarrow *nat-lsbf* \Rightarrow *nat-lsbf tm* **where**
subtract-nat-tm *xs ys = 1* **do** {
b \leftarrow *compare-nat-tm* *xs ys*;
if *b* **then** **return** [] **else** **do** {
(*fill-xs*, *fill-ys*) \leftarrow *make-same-length-tm* *xs ys*;
fill-ys-comp \leftarrow *map-tm Not-tm* *fill-ys*;
a \leftarrow *add-carry-tm* *True* *fill-xs* *fill-ys-comp*;
butlast-tm *a*
} }
}

lemma *val-subtract-nat-tm*[*simp*, *val-simp*]: *val* (*subtract-nat-tm* *xs ys*) = *xs* $-_n$ *ys*
by (*simp add: subtract-nat-tm-def subtract-nat-def Let-def split: prod.splits*)

lemma *time-map-tm-Not-tm*: *time* (*map-tm Not-tm* *xs*) = $2 * \text{length } xs + 1$
using *time-map-tm-constant*[*of xs Not-tm 1*] **by** *simp*

lemma *time-subtract-nat-tm-le*: *time* (*subtract-nat-tm* *xs ys*) $\leq 30 * \max (\text{length } xs) (\text{length } ys) + 48$

proof –

obtain *x1 x2* **where** *x12: make-same-length* *xs ys = (x1, x2)* **by** *fastforce*
note *x12-simps = make-same-length-correct*[*OF x12*[*symmetric*]]
then have *max12: max* (*length* *x1*) (*length* *x2*) = *max* (*length* *xs*) (*length* *ys*)

by *simp*

show *?thesis*

proof (*cases compare-nat* *xs ys*)

case *True*

then show *?thesis*

using *time-compare-nat-tm-le*[*of xs ys*]

by (*simp add: subtract-nat-tm-def*)

next

case *False*

then have *time* (*subtract-nat-tm* *xs ys*) =
Suc (*time* (*compare-nat-tm* *xs ys*) +
(*time* (*make-same-length-tm* *xs ys*) +
(*time* (*map-tm Not-tm* *x2*) +
(*time* (*add-carry-tm* *True* *x1* (*map Not* *x2*)) +
(*time* (*butlast-tm* (*add-carry* *True* *x1* (*map Not* *x2*)))))))))

by (*simp add: subtract-nat-tm-def x12*)

also have $\dots \leq 30 * \max (\text{length } xs) (\text{length } ys) + 48$

apply (*subst Suc-eq-plus1*)

apply (*estimation estimate: time-compare-nat-tm-le*)

apply (*estimation estimate: time-make-same-length-tm-le*)

```

apply (subst time-map-tm-Not-tm)
apply (estimation estimate: time-add-carry-tm-le)
apply (estimation estimate: time-butlast-tm-le)
apply (estimation estimate: time-inc-nat-tm-le)
apply (estimation estimate: length-add-carry-upper)
apply (subst length-map)+
apply (subst max12)+
apply (subst x12-simps)+
apply simp
done
finally show ?thesis .
qed
qed

```

9.7 (Grid) Multiplication

```

fun grid-mul-nat-tm :: nat-lsbf  $\Rightarrow$  nat-lsbf  $\Rightarrow$  nat-lsbf tm where
  grid-mul-nat-tm [] ys =1 return []
| grid-mul-nat-tm (False # xs) ys =1 do {
  r  $\leftarrow$  grid-mul-nat-tm xs ys;
  return (False # r)
}
| grid-mul-nat-tm (True # xs) ys =1 do {
  r  $\leftarrow$  grid-mul-nat-tm xs ys;
  add-nat-tm (False # r) ys
}

```

lemma val-grid-mul-nat-tm[simp, val-simp]: val (grid-mul-nat-tm xs ys) = xs *_n ys
by (induction xs ys rule: grid-mul-nat-tm.induct) simp-all

lemma euler-sum-bound: $\sum \{..(n::nat)\} \leq n * n$
by (induction n) simp-all

lemma time-grid-mul-nat-tm-le:

time (grid-mul-nat-tm xs ys) $\leq 8 * \text{length } xs * \max(\text{length } xs) (\text{length } ys) + 1$

proof –

have time (grid-mul-nat-tm xs ys) $\leq 2 * (\sum \{..length\ } xs) + \text{length } xs * (2 * \text{length } ys + 4) + 1$

proof (induction xs ys rule: grid-mul-nat-tm.induct)

case (1 ys)

then show ?case **by** simp

next

case (2 xs ys)

then show ?case **by** simp

next

case (3 xs ys)

then have time (grid-mul-nat-tm (True # xs) ys) \leq
time (grid-mul-nat-tm xs ys) +

```

    time (add-nat-tm (False # grid-mul-nat xs ys) ys) + 1 (is ?l ≤ ?i + - + 1)
  by simp
  also have ... ≤ ?i + 2 * max (1 + length (grid-mul-nat xs ys)) (length ys) + 4
  by (estimation estimate: time-add-nat-tm-le) simp
  also have ... ≤ ?i + 2 * (length xs + length ys + 1) + 4
  apply (estimation estimate: length-grid-mul-nat[of xs ys])
  by (simp-all add: length-grid-mul-nat)
  also have ... = ?i + 2 * (length (True # xs)) + 2 * length ys + 4
  by simp
  also have ... ≤ 2 * (∑ {..length (True # xs)}) + length (True # xs) * (2 *
length ys + 4) + 1
  using 3 by simp
  finally show ?case .
qed
  also have ... ≤ 2 * length xs * length xs + 2 * length xs * length ys + 4 * length
xs + 1
  by (estimation estimate: euler-sum-bound) (simp add: distrib-left)
  also have ... ≤ 6 * length xs * length xs + 2 * length xs * length ys + 1
  by (simp add: leI)
  also have ... ≤ 8 * length xs * max (length xs) (length ys) + 1
  by (simp add: add.commute add-mult-distrib nat-mult-max-right)
  finally show ?thesis .
qed

```

9.8 Syntax bundles

abbreviation *shift-right-tm-flip* where $\text{shift-right-tm-flip } xs \ n \equiv \text{shift-right-tm } n \ xs$

bundle *nat-lsbf-tm-syntax*

begin

```

  notation add-nat-tm (infixl +nt 65)
  notation compare-nat-tm (infixl ≤nt 50)
  notation subtract-nat-tm (infixl -nt 65)
  notation grid-mul-nat-tm (infixl *nt 70)
  notation shift-right-tm-flip (infixl >>nt 55)

```

end

bundle *no-nat-lsbf-tm-syntax*

begin

```

  no-notation add-nat-tm (infixl +nt 65)
  no-notation compare-nat-tm (infixl ≤nt 50)
  no-notation subtract-nat-tm (infixl -nt 65)
  no-notation grid-mul-nat-tm (infixl *nt 70)
  no-notation shift-right-tm-flip (infixl >>nt 55)

```

end

unbundle *nat-lsbf-tm-syntax*

```

end
theory Int-LSBF
  imports Nat-LSBF HOL-Algebra.IntRing
begin

```

10 Representing *int* in LSBF

10.1 Type definition

```

datatype sign = Positive | Negative
type-synonym int-lsbf = sign × nat-lsbf

```

10.2 Conversions

```

fun from-int :: int ⇒ int-lsbf where
  from-int x = (if x ≥ 0 then (Positive, from-nat (nat x)) else (Negative, from-nat
    (nat (-x))))
fun to-int :: int-lsbf ⇒ int where
  to-int (Positive, xs) = int (to-nat xs)
  | to-int (Negative, xs) = - int (to-nat xs)

```

```

lemma to-int-from-int[simp]: to-int (from-int x) = x
  by (cases x ≥ 0) simp-all

```

```

fun truncate-int :: int-lsbf ⇒ int-lsbf where
  truncate-int (Positive, xs) = (Positive, truncate xs)
  | truncate-int (Negative, xs) = (let ys = truncate xs in if ys = [] then (Positive, [])
    else (Negative, ys))

```

```

lemma to-int-truncate[simp]: to-int (truncate-int xs) = to-int xs
  by (induction xs rule: truncate-int.induct) (simp-all add: Let-def to-nat-zero-iff)

```

```

lemma truncate-from-int[simp]: truncate-int (from-int x) = from-int x
  apply (cases x ≥ 0)
  subgoal by simp
  subgoal unfolding Let-def
  proof -
    assume ¬ x ≥ 0
    then have to-nat (from-nat (nat (- x))) > 0 by simp
    then have truncate (from-nat (nat (- x))) ≠ [] using to-nat-zero-iff nless-le
  by blast
  then show ?thesis by simp
  qed
done

```

```

lemma pos-and-neg-imp-zero:
  assumes to-int (Positive, x) = to-int (Negative, y)
  shows to-nat x = 0 ∧ to-nat y = 0
proof -

```

have $to-int (Positive, x) \geq 0$ $to-int (Negative, y) \leq 0$ **by** *simp-all*
with *assms* **have** $to-int (Positive, x) = 0$ $to-int (Negative, y) = 0$ **by** *simp-all*
thus *?thesis* **by** *simp-all*
qed

lemma *to-int-eq-imp-truncate-int-eq*: $to-int (a, x) = to-int (b, y) \implies truncate-int (a, x) = truncate-int (b, y)$
apply (*cases a*; *cases b*)
subgoal by (*simp add: to-nat-eq-imp-truncate-eq*[*of x y*])
subgoal
using *pos-and-neg-imp-zero*[*of x y*] *to-nat-zero-iff*
by *fastforce*
subgoal using *to-nat-zero-iff* **by** (*simp add: Let-def*)
subgoal by (*simp add: to-nat-eq-imp-truncate-eq*[*of x y*])
done

lemma *from-int-to-int*: $from-int \circ to-int = truncate-int$
proof –
have ($\bigwedge x y. to-int x = to-int y \implies truncate-int x = truncate-int y$)
using *to-int-eq-imp-truncate-int-eq* **by** *auto*
thus *?thesis*
using *from-to-f-criterion*[*of to-int from-int truncate-int*]
using *truncate-from-int to-int-from-int*
using *comp-apply*
by *fastforce*
qed

interpretation *int-lsbf*: *abstract-representation from-int to-int truncate-int*
proof
show $to-int \circ from-int = id$
using *to-int-from-int comp-apply* **by** *fastforce*
next
show $from-int \circ to-int = truncate-int$
using *from-int-to-int comp-apply* **by** *fastforce*
qed

10.3 Addition

fun *add-int* :: *int-lsbf* \Rightarrow *int-lsbf* \Rightarrow *int-lsbf* **where**
add-int (*Negative, xs*) (*Negative, ys*) = (*Negative, add-nat xs ys*)
| *add-int* (*Positive, xs*) (*Positive, ys*) = (*Positive, add-nat xs ys*)
| *add-int* (*Positive, xs*) (*Negative, ys*) = (*if compare-nat xs ys then (Negative, subtract-nat ys xs) else (Positive, subtract-nat xs ys)*)
| *add-int* (*Negative, xs*) (*Positive, ys*) = (*if compare-nat xs ys then (Positive, subtract-nat ys xs) else (Negative, subtract-nat xs ys)*)

lemma *add-int-correct*: $to-int (add-int x y) = to-int x + to-int y$
apply (*induction x y rule: add-int.induct*)
subgoal by (*simp add: add-nat-correct*)

```

subgoal by (simp add: add-nat-correct)
apply (auto simp only: add-int.simps compare-nat-correct subtract-nat-correct
to-int.simps split: if-splits)
done

```

```

fun nat-mul-to-int-mul :: (nat-lsbf  $\Rightarrow$  nat-lsbf  $\Rightarrow$  nat-lsbf)  $\Rightarrow$  int-lsbf  $\Rightarrow$  int-lsbf
 $\Rightarrow$  int-lsbf where
nat-mul-to-int-mul f (x, xs) (y, ys) = ((if x = y then Positive else Negative), f xs
ys)

```

```

lemma nat-mul-to-int-mul-correct:
assumes  $\bigwedge x y. \text{to-nat } (f x y) = \text{to-nat } x * \text{to-nat } y$ 
shows  $\bigwedge x y xs ys. \text{to-int } (\text{nat-mul-to-int-mul } f (x, xs) (y, ys)) = \text{to-int } (x, xs) * \text{to-int } (y, ys)$ 
subgoal for x y xs ys
by (cases x; cases y) (simp-all add: assms)
done

```

10.4 Grid Multiplication

```

fun grid-mul-int where grid-mul-int x y = nat-mul-to-int-mul grid-mul-nat x y

```

```

corollary grid-mul-int-correct:  $\text{to-int } (\text{grid-mul-int } x y) = \text{to-int } x * \text{to-int } y$ 
using nat-mul-to-int-mul-correct[OF grid-mul-nat-correct]
by (metis grid-mul-int.elims surj-pair)

```

end

11 Karatsuba Multiplication

```

theory Karatsuba
imports ../Binary-Representations/Nat-LSBF ../Binary-Representations/Int-LSBF
../Estimation-Method
begin

```

This theory contains an implementation of the Karatsuba Multiplication on type *nat-lsbf*.

```

definition abs-diff :: nat-lsbf  $\Rightarrow$  nat-lsbf  $\Rightarrow$  nat-lsbf where
abs-diff x y = (x  $-_n$  y)  $+_n$  (y  $-_n$  x)

```

```

lemma abs-diff-correct:  $\text{int } (\text{to-nat } (\text{abs-diff } x y)) = \text{abs } (\text{int } (\text{to-nat } x) - \text{int } (\text{to-nat } y))$ 
unfolding abs-diff-def by (simp add: add-nat-correct subtract-nat-correct)

```

```

lemma abs-diff-length:  $\text{length } (\text{abs-diff } xs ys) \leq \max (\text{length } xs) (\text{length } ys)$ 

```

```

proof (cases compare-nat xs ys)

```

```

case True

```

```

then have xs  $-_n$  ys = [] by (simp add: subtract-nat-def)

```

```

then have abs-diff xs ys = ys  $-_n$  xs by (simp add: abs-diff-def add-nat-def)

```

```

then show ?thesis using length-subtract-nat-le[of ys xs] by simp
next
  case False
  then have  $ys \leq_n xs$  by (simp only: compare-nat-correct)
  then have  $ys -_n xs = []$  by (simp add: subtract-nat-def)
  then have  $\text{abs-diff } xs \ ys = xs -_n ys$  by (simp add: abs-diff-def add-nat-com
add-nat-def)
  then show ?thesis using length-subtract-nat-le[of xs ys] by simp
qed

```

For small inputs, implementations of Karatsuba Multiplication usually switch to grid multiplication. The threshold does not matter for the asymptotic running time, hence we will just arbitrarily choose 42 .

definition *karatsuba-lower-bound* :: nat **where**
karatsuba-lower-bound $\equiv 42$

lemma *karatsuba-lower-bound-requirement*:
karatsuba-lower-bound ≥ 1
unfolding *karatsuba-lower-bound-def* **by** simp

A first version of the algorithm assumes the input numbers have a length which is a power of 2. The function *karatsuba-on-power-of-2-length* takes the specified length as additional first argument.

```

fun karatsuba-on-power-of-2-length :: nat  $\Rightarrow$  nat-lsbf  $\Rightarrow$  nat-lsbf  $\Rightarrow$  nat-lsbf where
karatsuba-on-power-of-2-length k x y =
  (if  $k \leq \text{karatsuba-lower-bound}$ 
  then  $x *_n y$ 
  else let
    (x0, x1) = split x;
    (y0, y1) = split y;
    k-div-2 = (k div 2);
    prod0 = karatsuba-on-power-of-2-length k-div-2 x0 y0;
    prod1 = karatsuba-on-power-of-2-length k-div-2 x1 y1;
    prod2 = karatsuba-on-power-of-2-length k-div-2
      (fill k-div-2 (abs-diff x0 x1))
      (fill k-div-2 (abs-diff y0 y1));
    add01 = prod0 +n prod1;
    r = (if ( $x1 \leq_n x0$ ) = ( $y1 \leq_n y0$ ))
      then add01 -n prod2
      else add01 +n prod2)
  in prod0 +n (r >>n k-div-2) +n (prod1 >>n k))

```

declare *karatsuba-on-power-of-2-length.simps*[simp del]

```

locale karatsuba-context =
  fixes k l :: nat
  fixes x y :: nat-lsbf
  assumes k-power-of-2:  $k = 2 \wedge l$ 
  assumes length-x:  $\text{length } x = k$ 

```

assumes *length-y*: $\text{length } y = k$
assumes *recursion-condition*: $\neg k \leq \text{karatsuba-lower-bound}$
begin

definition *x0* **where** $x0 = \text{fst } (\text{split } x)$
definition *x1* **where** $x1 = \text{snd } (\text{split } x)$
definition *y0* **where** $y0 = \text{fst } (\text{split } y)$
definition *y1* **where** $y1 = \text{snd } (\text{split } y)$
definition *k-div-2* **where** $k\text{-div-2} = k \text{ div } 2$
definition *prod0* **where** $\text{prod0} = \text{karatsuba-on-power-of-2-length } k\text{-div-2 } x0 \ y0$
definition *prod1* **where** $\text{prod1} = \text{karatsuba-on-power-of-2-length } k\text{-div-2 } x1 \ y1$
definition *prod2* **where** $\text{prod2} = \text{karatsuba-on-power-of-2-length } k\text{-div-2}$
 (fill *k-div-2* (*abs-diff* *x0* *x1*))
 (fill *k-div-2* (*abs-diff* *y0* *y1*))
definition *add01* **where** $\text{add01} = \text{prod0} +_n \text{prod1}$
definition *r* **where** $r = (\text{if } (x1 \leq_n x0) = (y1 \leq_n y0)$
 then $\text{add01} -_n \text{prod2}$
 else $\text{add01} +_n \text{prod2}$)

lemma *split-x*: $\text{split } x = (x0, x1)$ **using** *x0-def* *x1-def* **by** *simp*
lemma *split-y*: $\text{split } y = (y0, y1)$ **using** *y0-def* *y1-def* **by** *simp*

lemmas *defs1* = *split-x split-y*
lemmas *defs2* = *prod0-def prod1-def prod2-def k-div-2-def add01-def r-def*

lemma *recursive*: $\text{karatsuba-on-power-of-2-length } k \ x \ y =$
 $\text{prod0} +_n (r \gg_n k\text{-div-2}) +_n (\text{prod1} \gg_n k)$
unfolding *karatsuba-on-power-of-2-length.simps*[of *k x y*]
using *defs1 defs2 recursion-condition*
by (*simp only: if-False Let-def case-prod-conv*)

lemma *l-ge-1*: $l \geq 1$
using *karatsuba-lower-bound-requirement recursion-condition k-power-of-2*
by (*cases l; simp*)

lemma *k-even*: $k \bmod 2 = 0$
using *k-power-of-2 l-ge-1* **by** *simp*

lemma *k-div-2*: $k\text{-div-2} = 2 \wedge (l - 1)$
unfolding *k-div-2-def* **using** *k-power-of-2 l-ge-1* **by** (*simp add: power-diff*)

lemma *k-div-2-less-k*: $k\text{-div-2} < k$
unfolding *k-div-2-def* **using** *k-power-of-2* **by** *simp*

lemma *length-x-split*: $\text{length } x0 = k\text{-div-2} \ \text{length } x1 = k\text{-div-2}$
unfolding *k-div-2-def* **using** *k-even length-split[OF - split-x]* *length-x* **by** *argo+*

lemma *length-y-split*: $\text{length } y0 = k\text{-div-2} \ \text{length } y1 = k\text{-div-2}$
unfolding *k-div-2-def* **using** *k-even length-split[OF - split-y]* *length-y* **by** *argo+*


```

lemma length-abs-diff-x0-x1: length (abs-diff x0 x1) ≤ k-div-2
  using abs-diff-length[of x0 x1] length-x-split by simp
lemma length-fill-abs-diff-x0-x1: length (fill k-div-2 (abs-diff x0 x1)) = k-div-2
  by (intro length-fill length-abs-diff-x0-x1)

lemma length-abs-diff-y0-y1: length (abs-diff y0 y1) ≤ k-div-2
  using abs-diff-length[of y0 y1] length-y-split by simp
lemma length-fill-abs-diff-y0-y1: length (fill k-div-2 (abs-diff y0 y1)) = k-div-2
  by (intro length-fill length-abs-diff-y0-y1)

lemmas IH-prems1 = recursion-condition split-x[symmetric] refl split-y[symmetric]
refl k-div-2-def
  k-div-2 length-x-split(1) length-y-split(1)

lemmas IH-prems2 = recursion-condition split-x[symmetric] refl split-y[symmetric]
refl k-div-2-def
  prod0-def k-div-2 length-x-split(2) length-y-split(2)

lemmas IH-prems3 = recursion-condition split-x[symmetric] refl split-y[symmetric]
refl k-div-2-def
  prod0-def prod1-def k-div-2 length-fill-abs-diff-x0-x1 length-fill-abs-diff-y0-y1

end

lemma karatsuba-on-power-of-2-length-correct:
  assumes k = 2 ^ l
  assumes length x = k length y = k
  shows to-nat (karatsuba-on-power-of-2-length k x y) = to-nat x * to-nat y
using assms proof (induction k x y arbitrary: l rule: karatsuba-on-power-of-2-length.induct)
  case (1 k x y l)
  show ?case
  proof (cases k ≤ karatsuba-lower-bound)
    case True
    then show ?thesis
    unfolding karatsuba-on-power-of-2-length.simps[of k x y]
    by (simp add: grid-mul-nat-correct)
  next
  case False
  then interpret r: karatsuba-context k l x y using 1.prems
    by (unfold-locales; simp)
  from r.l-ge-1 obtain l' where l = Suc l'
    by (metis less-eqE plus-1-eq-Suc)
  then have k div 2 = 2 ^ l' using ⟨k = 2 ^ l⟩ by simp

  have to-nat-x: to-nat x = to-nat r.x0 + 2 ^ (k div 2) * to-nat r.x1
    unfolding r.k-div-2-def[symmetric]
    using app-split[OF r.split-x] to-nat-app[of r.x0 r.x1] r.length-x-split by algebra

```

have *to-nat-y*: $to\text{-}nat\ y = to\text{-}nat\ r.y0 + 2 \wedge (k\ div\ 2) * to\text{-}nat\ r.y1$
unfolding *r.k-div-2-def[symmetric]*
using *app-split[OF r.split-y] to-nat-app[of r.y0 r.y1] r.length-y-split* **by** *algebra*

have *4*: $to\text{-}nat\ r.prod0 = to\text{-}nat\ r.x0 * to\text{-}nat\ r.y0$
unfolding *r.prod0-def*
by (*intro 1(1)[OF r.IH-prems1]*)

have *5*: $to\text{-}nat\ r.prod1 = to\text{-}nat\ r.x1 * to\text{-}nat\ r.y1$
unfolding *r.prod1-def*
by (*intro 1(2)[OF r.IH-prems2]*)

have $to\text{-}nat\ r.prod2 = to\text{-}nat\ (fill\ r.k\text{-}div\ 2\ (abs\text{-}diff\ r.x0\ r.x1)) * to\text{-}nat\ (fill\ r.k\text{-}div\ 2\ (abs\text{-}diff\ r.y0\ r.y1))$
unfolding *r.prod2-def*
by (*intro 1(3)[OF r.IH-prems3]*)

hence $int\ (to\text{-}nat\ r.prod2) = abs\ (int\ (to\text{-}nat\ r.x0) - int\ (to\text{-}nat\ r.x1)) * abs\ (int\ (to\text{-}nat\ r.y0) - int\ (to\text{-}nat\ r.y1))$
using *abs-diff-correct* **by** *simp*

then have $int\ (to\text{-}nat\ r.prod2) = abs\ ((int\ (to\text{-}nat\ r.x0) - int\ (to\text{-}nat\ r.x1)) * (int\ (to\text{-}nat\ r.y0) - int\ (to\text{-}nat\ r.y1)))$
by (*subst abs-mult, assumption*)

then have *6*: (*if* (*compare-nat r.x1 r.x0*) = (*compare-nat r.y1 r.y0*) *then* $int\ (to\text{-}nat\ r.prod2)$ *else* $- int\ (to\text{-}nat\ r.prod2)$) = $(int\ (to\text{-}nat\ r.x0) - int\ (to\text{-}nat\ r.x1)) * (int\ (to\text{-}nat\ r.y0) - int\ (to\text{-}nat\ r.y1))$

apply (*cases to-nat r.x0 ≥ to-nat r.x1; cases to-nat r.y0 ≥ to-nat r.y1*)

by (*simp-all add: compare-nat-correct mult-nonneg-nonpos mult-nonneg-nonpos2 mult-nonpos-nonpos*)

have *7*: $int\ (to\text{-}nat\ r.r) = int\ (to\text{-}nat\ r.x0) * int\ (to\text{-}nat\ r.y1) + int\ (to\text{-}nat\ r.x1) * int\ (to\text{-}nat\ r.y0)$

proof (*cases (r.x1 ≤_n r.x0) = (r.y1 ≤_n r.y0)*)

case *True*

then have *int-p*: $int\ (to\text{-}nat\ r.r) = int\ (to\text{-}nat\ r.prod0 + to\text{-}nat\ r.prod1 - to\text{-}nat\ r.prod2)$

unfolding *r.r-def r.add01-def*
by (*simp add: subtract-nat-correct add-nat-correct*)

have *int-prod2*: $int\ (to\text{-}nat\ r.prod2) = (int\ (to\text{-}nat\ r.x0) - int\ (to\text{-}nat\ r.x1)) * (int\ (to\text{-}nat\ r.y0) - int\ (to\text{-}nat\ r.y1))$

using *6 True* **by** *simp*

have $-(int\ (to\text{-}nat\ r.x0) * int\ (to\text{-}nat\ r.y1)) \leq int\ (to\text{-}nat\ r.x1) * int\ (to\text{-}nat\ r.y0)$

apply (*intro order.trans[of - (int (to-nat r.x0) * int (to-nat r.y1)) 0 int (to-nat r.x1) * int (to-nat r.y0)]*)

by *simp-all*

then have $to\text{-}nat\ r.prod0 + to\text{-}nat\ r.prod1 \geq to\text{-}nat\ r.prod2$

apply (*intro iffD1[OF zle-int]*)

by (*simp add: 4 5 int-prod2 left-diff-distrib right-diff-distrib*)

then have $int\ (to\text{-}nat\ r.r) = int\ (to\text{-}nat\ r.prod0) + int\ (to\text{-}nat\ r.prod1) - int\ (to\text{-}nat\ r.prod2)$

using *int-p* **by** *simp*

then show *?thesis* **using** *int-prod2* **by** (*simp add: left-diff-distrib right-diff-distrib*
4 5)
next
case *False*
then have $\text{int (to-nat r.r) = int (to-nat r.prod0) + int (to-nat r.prod1) + int (to-nat r.prod2)}$
unfolding *r.r-def*
by (*simp add: add-nat-correct r.add01-def*)
moreover from *False 6* **have** $-\text{int (to-nat r.prod2) = (int (to-nat r.x0) - int (to-nat r.x1)) * (int (to-nat r.y0) - int (to-nat r.y1))}$
by *simp*
then have $\text{int (to-nat r.prod2) = - (int (to-nat r.x0) - int (to-nat r.x1)) * (int (to-nat r.y0) - int (to-nat r.y1))}$
by *linarith*
ultimately show *?thesis* **by** (*simp add: 4 5 left-diff-distrib right-diff-distrib*)
qed

from *r.recursive* **have** $\text{int (to-nat (karatsuba-on-power-of-2-length k x y)) = int (to-nat (r.prod0 +_n (r.r >>_n r.k-div-2) +_n (r.prod1 >>_n k)))}$ **by** *simp*
also have $\dots = \text{int (to-nat r.prod0) + int (to-nat (shift-right r.k-div-2 r.r)) + int (to-nat (shift-right k r.prod1))}$
by (*simp add: add-nat-correct*)
also have $\dots = \text{int (to-nat r.prod0) + int (2 ^ (k div 2) * to-nat r.r) + int (2 ^ k * to-nat r.prod1)}$
by (*simp only: to-nat-shift-right r.k-div-2-def*)
also have $\dots = \text{int (to-nat r.prod0) + 2 ^ (k div 2) * int (to-nat r.r) + 2 ^ k * int (to-nat r.prod1)}$
by *simp*
also have $\dots = \text{int (to-nat r.x0) * int (to-nat r.y0) + 2 ^ (k div 2) * (int (to-nat r.x0) * int (to-nat r.y1) + int (to-nat r.x1) * int (to-nat r.y0)) + 2 ^ k * int (to-nat r.x1) * int (to-nat r.y1)}$
using *7 4 5*
by *simp*
also have $\dots = (\text{int (to-nat r.x0) + 2 ^ (k div 2) * (int (to-nat r.x1))}) * (\text{int (to-nat r.y0) + 2 ^ (k div 2) * (int (to-nat r.y1))})$
proof $-$
have $2 * (k \text{ div } 2) = k$
using *r.k-even* **by** *force*
have $(\text{int (to-nat r.x0) + 2 ^ (k div 2) * (int (to-nat r.x1))}) * (\text{int (to-nat r.y0) + 2 ^ (k div 2) * (int (to-nat r.y1))})$
 $= \text{int (to-nat r.x0) * int (to-nat r.y0)}$
 $+ (2::\text{int}) ^ (k \text{ div } 2) * (\text{int (to-nat r.x1)}) * (\text{int (to-nat r.y0)})$
 $+ (\text{int (to-nat r.x0)}) * 2 ^ (k \text{ div } 2) * (\text{int (to-nat r.y1)})$
 $+ (2::\text{int}) ^ (k \text{ div } 2) * (\text{int (to-nat r.x1)}) * 2 ^ (k \text{ div } 2) * (\text{int (to-nat r.y1)})$
using *distrib-left[of (int (to-nat r.x0) + 2 ^ (k div 2) * (int (to-nat r.x1)))]*
 $\text{int (to-nat r.y0) } 2 ^ (k \text{ div } 2) * (\text{int (to-nat r.y1)})]$
by (*simp add: ring-class.ring-distrib(2)*)

```

also have ... = int (to-nat r.x0) * int (to-nat r.y0)
  + (2::int) ^ (k div 2) * (int (to-nat r.x1)) * (int (to-nat r.y0))
  + (int (to-nat r.x0)) * 2 ^ (k div 2) * (int (to-nat r.y1))
  + ((2::int) ^ (k div 2) * 2 ^ (k div 2)) * (int (to-nat r.x1)) * (int (to-nat
r.y1))
  by simp
also have (2::int) ^ (k div 2) * 2 ^ (k div 2) = 2 ^ k
  using power-add[of 2::int k div 2 k div 2, symmetric]
  using ⟨2 * (k div 2) = k⟩
  by simp
finally have (int (to-nat r.x0) + 2 ^ (k div 2) * (int (to-nat r.x1)))
  * (int (to-nat r.y0) + 2 ^ (k div 2) * (int (to-nat r.y1)))
  = int (to-nat r.x0) * int (to-nat r.y0)
  + 2 ^ (k div 2) * (int (to-nat r.x1)) * (int (to-nat r.y0))
  + (int (to-nat r.x0)) * 2 ^ (k div 2) * (int (to-nat r.y1))
  + (2::int) ^ k * (int (to-nat r.x1)) * (int (to-nat r.y1)) by simp
also have ... = int (to-nat r.x0) * int (to-nat r.y0)
  + ((2::int) ^ (k div 2) * (int (to-nat r.x1)) * (int (to-nat r.y0)))
  + (2::int) ^ (k div 2) * (int (to-nat r.x0)) * (int (to-nat r.y1))
  + (2::int) ^ k * (int (to-nat r.x1)) * (int (to-nat r.y1))
  by simp
also have ... = int (to-nat r.x0) * int (to-nat r.y0)
  + (2::int) ^ (k div 2) * (int (to-nat r.x1)) * int (to-nat r.y0) + int (to-nat
r.x0) * int (to-nat r.y1))
  + (2::int) ^ k * (int (to-nat r.x1)) * (int (to-nat r.y1))
  using distrib-left[of (2::int) ^ (k div 2)] by simp
finally show ?thesis by simp
qed
also have ... = int (to-nat x) * int (to-nat y)
  by (simp add: to-nat-x to-nat-y)
finally have int (to-nat (karatsuba-on-power-of-2-length k x y)) = int (to-nat
x * to-nat y)
  by simp
thus ?thesis by presburger
qed
qed

function len-kar-bound where
len-kar-bound l = (if 2 ^ l ≤ karatsuba-lower-bound then 2 * karatsuba-lower-bound
else 2 ^ l + len-kar-bound (l - 1) + 4)
  by pat-completeness auto
termination
apply (relation Wellfounded.measure (λl. l))
subgoal by simp
subgoal for l
using karatsuba-lower-bound-requirement by (cases l; simp)
done

declare len-kar-bound.simps[simp del]

```

```

lemma length-karatsuba-on-power-of-2-aux:
  assumes  $k = 2 \wedge l$ 
  assumes  $\text{length } x = k \text{ length } y = k$ 
  shows  $\text{length } (\text{karatsuba-on-power-of-2-length } k \ x \ y) \leq \text{len-kar-bound } l$ 
  using assms proof (induction  $k \ x \ y$  arbitrary:  $l$  rule: karatsuba-on-power-of-2-length.induct)
  case ( $1 \ k \ x \ y$ )
  then show ?case
  proof (cases  $k \leq \text{karatsuba-lower-bound}$ )
    case True
      then have  $\text{karatsuba-on-power-of-2-length } k \ x \ y = \text{grid-mul-nat } x \ y$ 
        unfolding karatsuba-on-power-of-2-length.simps[of  $k \ x \ y$ ] by argo
      also have  $\text{length } \dots \leq \text{length } x + \text{length } y$ 
        by (rule length-grid-mul-nat)
      also have  $\dots = 2 * k$  using  $1$  by linarith
      also have  $\dots \leq \text{len-kar-bound } l$ 
        unfolding len-kar-bound.simps[of  $l$ ] using  $1.\text{prems}$  True by simp
      finally show ?thesis .
    next
      case False
        then interpret  $r$ : karatsuba-context  $k \ l \ x \ y$  using  $1.\text{prems}$  by unfold-locales
  simp-all
  from  $r.\text{recursive}$  have  $\text{length } (\text{karatsuba-on-power-of-2-length } k \ x \ y) =$ 
     $\text{length } (r.\text{prod0} +_n (r.r \gg_n r.k\text{-div-2}) +_n$ 
       $(r.\text{prod1} \gg_n k))$ 
    by argo
  also have  $\dots \leq \max (\max (\text{length } r.\text{prod0})$ 
     $(2 \wedge (l - 1) +$ 
       $\max (\max (\text{length } r.\text{prod0}) (\text{length } r.\text{prod1}) + 1) (\text{length } r.\text{prod2}) + 1)$ 
     $+ 1)$ 
     $(k + \text{length } r.\text{prod1}) + 1$ 
    unfolding  $r.r\text{-def}$   $r.\text{add01-def}$ 
    apply (estimation estimate: length-add-nat-upper)
    apply (estimation estimate: length-add-nat-upper)
    unfolding length-shift-right  $r.k\text{-div-2}$  if-distrib[of length]
    apply (estimation estimate: if-le-max)
    apply (estimation estimate: length-add-nat-upper)
    apply (estimation estimate: length-subtract-nat-le)
    apply (estimation estimate: length-add-nat-upper)
    by simp
  also have  $\dots \leq \max (\max (\text{len-kar-bound } (l - 1))$ 
     $(2 \wedge (l - 1) +$ 
       $\max (\max (\text{len-kar-bound } (l - 1)) (\text{len-kar-bound } (l - 1)) + 1)$ 
       $(\text{len-kar-bound } (l - 1)) + 1) + 1)$ 
     $(k + \text{len-kar-bound } (l - 1)) + 1$ 
    unfolding  $r.\text{prod0-def}$   $r.\text{prod1-def}$   $r.\text{prod2-def}$ 
    apply (estimation estimate:  $1.IH(1)$ [OF  $r.IH\text{-prems1}$ ])
    apply (estimation estimate:  $1.IH(2)$ [OF  $r.IH\text{-prems2}$ ])
    apply (estimation estimate:  $1.IH(3)$ [OF  $r.IH\text{-prems3}$ ])

```

```

    by (rule order.refl)
  also have ... = max (2 ^ (l - 1) + len-kar-bound (l - 1) + 3)
    (2 ^ l + len-kar-bound (l - 1)) + 1
    unfolding max.idem r.k-power-of-2 by (simp del: One-nat-def)
  also have ... ≤ (2 ^ l + len-kar-bound (l - 1) + 3) + 1
  apply (intro add-mono order.refl)
  apply (intro max.boundedI)
  subgoal
    apply (intro add-mono order.refl) by simp
  subgoal by simp
  done
  also have ... = len-kar-bound l
    unfolding len-kar-bound.simps[of l] using False r.k-power-of-2 by simp
  finally show ?thesis .
qed
qed

lemma len-kar-bound-le: len-kar-bound l ≤ 6 * 2 ^ l + 2 * karatsuba-lower-bound
proof (induction l rule: less-induct)
  case (less l)
  then show ?case
  proof (cases 2 ^ l ≤ karatsuba-lower-bound)
    case True
    then show ?thesis
    unfolding len-kar-bound.simps[of l] by simp
  next
    case False
    then have l - 1 < l using karatsuba-lower-bound-requirement by (cases l;
simp)
    then have l > 0 by simp
    from False have len-kar-bound l = 2 ^ l + len-kar-bound (l - 1) + 4
    unfolding len-kar-bound.simps[of l] by argo
    also have ... ≤ 2 ^ l + (6 * 2 ^ (l - 1) + 2 * karatsuba-lower-bound) + 4
    using less[OF ⟨l - 1 < l⟩] by simp
    also have ... = 2 * (2 ^ (l - 1)) + (6 * 2 ^ (l - 1) + 2 * karatsuba-lower-bound)
+ 4
    unfolding power-Suc[symmetric] Suc-diff-1[OF ⟨l > 0⟩] by (rule refl)
    also have ... = 8 * 2 ^ (l - 1) + 4 + 2 * karatsuba-lower-bound by simp
    also have ... ≤ 8 * 2 ^ (l - 1) + 4 * 2 ^ (l - 1) + 2 * karatsuba-lower-bound
by simp
    also have ... = 12 * 2 ^ (l - 1) + 2 * karatsuba-lower-bound by simp
    also have ... = 6 * 2 ^ l + 2 * karatsuba-lower-bound
    using Suc-diff-1[OF ⟨l > 0⟩, symmetric] power-Suc[of 2::nat l - 1] by simp
    finally show ?thesis .
  qed
qed

```

The following is a pretty crude estimate for the length of the result of our Karatsuba implementation, but it suffices for our purposes.

lemma *length-karatsuba-on-power-of-2-length-le*:
assumes $k = 2 \wedge l$
assumes $\text{length } x = k \text{ length } y = k$
shows $\text{length } (\text{karatsuba-on-power-of-2-length } k \ x \ y) \leq 6 * k + 2 * \text{karatsuba-lower-bound}$
using *order.trans[OF length-karatsuba-on-power-of-2-aux[OF assms] len-kar-bound-le]*
unfolding *assms* .

In order to multiply two integers of arbitrary length using Karatsuba multiplication, the input numbers can just be zero-padded.

fun *karatsuba-mul-nat* :: *nat-lsbf* \Rightarrow *nat-lsbf* \Rightarrow *nat-lsbf* **where**
karatsuba-mul-nat $x \ y = (\text{let } k = \text{next-power-of-2 } (\max (\text{length } x) (\text{length } y)) \text{ in } \text{karatsuba-on-power-of-2-length } k \ (\text{fill } k \ x) \ (\text{fill } k \ y))$

We verify the correctness of Karatsuba multiplication:

theorem *karatsuba-mul-nat-correct*: $\text{to-nat } (\text{karatsuba-mul-nat } x \ y) = \text{to-nat } x * \text{to-nat } y$

proof –

define k **where** $k = \text{next-power-of-2 } (\max (\text{length } x) (\text{length } y))$
then obtain l **where** $k = 2 \wedge l$ **using** *next-power-of-2-is-power-of-2* **by** *blast*
have 1 : $\text{to-nat } (\text{fill } k \ x) = \text{to-nat } x \ \text{to-nat } (\text{fill } k \ y) = \text{to-nat } y$ **by** *simp-all*
have $k \geq \text{length } x \ k \geq \text{length } y$
using *next-power-of-2-lower-bound[of max (length x) (length y)] k-def*
by *simp-all*
hence $\text{length } (\text{fill } k \ x) = k \ \text{length } (\text{fill } k \ y) = k$ **using** *length-fill* **by** *simp-all*
show *?thesis* **unfolding** *k-def[symmetric] karatsuba-lower-bound-def*
using *karatsuba-on-power-of-2-length-correct[OF <k = 2 ^ l> <length (fill k x) = k> <length (fill k y) = k>]*
by (*simp only: karatsuba-mul-nat.simps Let-def k-def[symmetric] to-nat-fill*)
qed

lemma *length-karatsuba-mul-nat-le*: $\text{length } (\text{karatsuba-mul-nat } x \ y) \leq 12 * \max (\text{length } x) (\text{length } y) + (6 + 2 * \text{karatsuba-lower-bound})$

proof –

let $?m = \max (\text{length } x) (\text{length } y)$
define k **where** $k = \text{next-power-of-2 } ?m$
then obtain l **where** $k = 2 \wedge l$ **using** *next-power-of-2-is-power-of-2* **by** *auto*
from *k-def* **have** $?m \leq k$ **using** *next-power-of-2-lower-bound* **by** *simp*
from *k-def* **have** $\text{karatsuba-mul-nat } x \ y = \text{karatsuba-on-power-of-2-length } k \ (\text{fill } k \ x) \ (\text{fill } k \ y)$
unfolding *karatsuba-mul-nat.simps Let-def* **by** *argo*
also have $\text{length } \dots \leq 6 * k + 2 * \text{karatsuba-lower-bound}$
apply (*intro length-karatsuba-on-power-of-2-length-le[OF <k = 2 ^ l>] length-fill*)
subgoal using $\langle ?m \leq k \rangle$ **by** *simp*
subgoal using $\langle ?m \leq k \rangle$ **by** *simp*
done
also have $\dots \leq 6 * (2 * ?m + 1) + 2 * \text{karatsuba-lower-bound}$
apply (*intro add-mono mult-le-mono order.refl*)
unfolding *k-def* **by** (*rule next-power-of-2-upper-bound'*)

```

also have ... = 12 * ?m + (6 + 2 * karatsuba-lower-bound)
  by simp
finally show ?thesis .
qed

```

Formally, we only implemented Karatsuba multiplication on natural numbers (not all integers). However, this does not really matter, as the multiplication can just be lifted to the integers. This lifting has already been done on other types, but for the sake of completeness we will just add it here as well:

```

fun karatsuba-mul-int where
  karatsuba-mul-int x y = nat-mul-to-int-mul karatsuba-mul-nat x y

```

```

corollary karatsuba-mul-int-correct:
  to-int (karatsuba-mul-int x y) = to-int x * to-int y
  using nat-mul-to-int-mul-correct[of karatsuba-mul-nat] karatsuba-mul-nat-correct
  by (metis karatsuba-mul-int.simps surj-pair)

```

```

end

```

12 Running Time of Karatsuba Multiplication

```

theory Karatsuba-TM
  imports Karatsuba ../Binary-Representations/Nat-LSBF-TM
  ../Estimation-Method
begin

```

This theory contains a time monad version of Karatsuba multiplication, which is used to verify the asymptotic running time of $\mathcal{O}(n^{\log_2 3})$.

```

definition abs-diff-tm :: nat-lsbf  $\Rightarrow$  nat-lsbf  $\Rightarrow$  nat-lsbf tm where
  abs-diff-tm xs ys =1 do {
    r1  $\leftarrow$  xs -nt ys;
    r2  $\leftarrow$  ys -nt xs;
    r1 +nt r2
  }

```

```

lemma val-abs-diff-tm[simp, val-simp]: val (abs-diff-tm xs ys) = abs-diff xs ys
  by (simp add: abs-diff-tm-def abs-diff-def)

```

```

lemma time-abs-diff-tm-le: time (abs-diff-tm xs ys)  $\leq$  62 * max (length xs) (length
  ys) + 100

```

```

proof -

```

```

  have time (abs-diff-tm xs ys)  $\leq$  time (xs -nt ys) + time (ys -nt xs) +
    time ((xs -n ys) +nt (ys -n xs)) + 1

```

```

  by (simp add: abs-diff-tm-def)

```

```

  also have ...  $\leq$  62 * max (length xs) (length ys) + 100

```

```

  apply (estimation estimate: time-subtract-nat-tm-le)

```

```

  apply (estimation estimate: time-subtract-nat-tm-le)

```


apply (*estimation estimate: time-add-nat-tm-le*)
using *length-subtract-nat-le*[of *xs ys*] *length-subtract-nat-le*[of *ys xs*]
by *linarith*
finally show *?thesis* .
qed

context *karatsuba-context*
begin

definition *fill-abs-diff-x* **where** *fill-abs-diff-x* = *fill k-div-2 (abs-diff x0 x1)*
definition *fill-abs-diff-y* **where** *fill-abs-diff-y* = *fill k-div-2 (abs-diff y0 y1)*
definition *sgnx* **where** *sgnx* = (*x1* ≤_{*n*} *x0*)
definition *sgny* **where** *sgny* = (*y1* ≤_{*n*} *y0*)
definition *sgnxy* **where** *sgnxy* = (*sgnx* = *sgny*)
definition *r'* **where** *r'* = (*if sgnxy then add01 -_n prod2 else add01 +_n prod2*)
definition *sr* **where** *sr* = *r >>_n k-div-2*
definition *add0sr* **where** *add0sr* = *prod0 +_n sr*
definition *s1* **where** *s1* = *prod1 >>_n k*

lemma *r-r'*: *r = r'*
unfolding *r-def r'-def sgnxy-def sgnx-def sgny-def* **by** *argo*

lemmas *defs3* = *fill-abs-diff-x-def fill-abs-diff-y-def sgnx-def sgny-def sgnxy-def r-r'*
r'-def sr-def add0sr-def s1-def

end

lemma *add-nat-carry-aux*:
assumes *length x* ≤ *k*
assumes *length y* ≤ *k*
assumes *length (x +_n y)* = *k + 1*
shows *max (length x) (length y) = k Nat-LSBF.to-nat x + Nat-LSBF.to-nat y*
≥ *2 ^ k*
proof –
have *length x = k ∨ length y = k*
proof (*rule ccontr*)
assume ¬ (*length x = k ∨ length y = k*)
then have *max (length x) (length y) < k* **using** *assms* **by** *simp*
then have *length (add-nat x y) < k + 1* **using** *length-add-nat-upper*[of *x y*]
by *linarith*
then show *False* **using** *assms* **by** *simp*
qed
then show *max (length x) (length y) = k* **using** *assms* **by** *linarith*
then obtain *z* **where** *add-nat x y = z @ [True]*
using *add-nat-last-bit-True* *assms* **by** *blast*
from *this[symmetric]* **have** *Nat-LSBF.to-nat x + Nat-LSBF.to-nat y ≥ 2 ^ length*
z
using *add-nat-correct*[of *x y*] *to-nat-length-lower-bound*[of *z*] **by** *argo*
also have *2 ^ length z = 2 ^ k* **using** *<add-nat x y = z @ [True]>* *assms* **by** *simp*

```

finally show Nat-LSBF.to-nat x + Nat-LSBF.to-nat y ≥ 2 ^ k by simp
qed

context begin

private fun f where
f k = (if k ≤ karatsuba-lower-bound then 2 * k else f (k div 2) + k + 4)

declare f.simps[simp del]

private lemma f-linear: f k ≤ 6 * k
  apply (induction k rule: f.induct)
  subgoal for k
    apply (cases k ≤ karatsuba-lower-bound)
    subgoal by (simp add: f.simps[of k])
    subgoal premises prems
    proof (cases k ≥ 5)
      case True
        then show ?thesis using prems unfolding f.simps[of k] by simp
      next
        case False
          then consider k = 2 | k = 3 | k = 4 using prems karatsuba-lower-bound-requirement
by linarith
        then show ?thesis using prems unfolding f.simps[of k] by fastforce
    qed
  done
done

private lemma f-bound:
  assumes k = 2 ^ l
  assumes length x = k
  assumes length y = k
  shows length (karatsuba-on-power-of-2-length k x y) ≤ f k
  using assms
proof (induction k x y arbitrary: l rule: karatsuba-on-power-of-2-length.induct)
  case (1 k x y)
  show ?case
  proof (cases k ≤ karatsuba-lower-bound)
    case True
      then show ?thesis unfolding karatsuba-on-power-of-2-length.simps[of k x y]
        using length-grid-mul-nat[of x y] 1.prems f.simps[of k] by simp
    next
      case False
        then interpret r : karatsuba-context k l x y
          using 1.prems by (unfold-locals; simp)
        have len0: length r.prod0 ≤ f (k div 2)
          unfolding r.prod0-def r.k-div-2-def[symmetric]
          by (intro 1(1)[OF r.IH-prems1])
        have len1: length r.prod1 ≤ f (k div 2)

```

```

    unfolding r.prod1-def r.k-div-2-def[symmetric]
  by (intro 1(2)[OF r.IH-prems2])
  have len2: length r.prod2 ≤ f (k div 2)
    unfolding r.prod2-def r.k-div-2-def[symmetric]
  by (intro 1(3)[OF r.IH-prems3])

  have len-p01: length (r.prod0 +n r.prod1) ≤ f (k div 2) + 1
    using length-add-nat-upper[of r.prod0 r.prod1] len0 len1 by linarith
  then have length (r.prod0 +n r.prod1 +n r.prod2) ≤ f (k div 2) + 2
    using length-add-nat-upper[of r.prod0 +n r.prod1 r.prod2] len2 by linarith
  moreover have length (r.prod0 +n r.prod1 -n r.prod2) ≤ f (k div 2) + 1
    using length-subtract-nat-le[of r.prod0 +n r.prod1 r.prod2] len-p01 len2
  by linarith
  ultimately have lenif: length (if r.sgnxy then r.prod0 +n r.prod1 -n r.prod2
    else r.prod0 +n r.prod1 +n r.prod2) ≤ f (k div 2) + 2 (is length ?if ≤
-)
  by simp

  have length (karatsuba-on-power-of-2-length k x y) ≤ max (r.k-div-2 + f (k div
2)) (k + f (k div 2)) + 4
    unfolding r.recursive
  apply (estimation estimate: length-add-nat-upper)
  apply (subst length-shift-right)
  apply (estimation estimate: length-add-nat-upper)
  apply (subst length-shift-right)
  unfolding r.r-def r.add01-def
  apply (subst if-distrib[of length])
  apply (estimation estimate: length-add-nat-upper)
  apply (estimation estimate: length-subtract-nat-le)
  apply (estimation estimate: length-add-nat-upper)
  apply (estimation estimate: len0)
  apply (estimation estimate: len1)
  apply (estimation estimate: len2)
  by auto
  also have ... = k + f (k div 2) + 4
    using r.k-div-2-less-k by simp
  finally show ?thesis unfolding f.simps[of k] using False by simp
qed
qed

lemma length-karatsuba-on-power-of-2-length:
  assumes k = 2 ^ l
  assumes length x = k
  assumes length y = k
  shows length (karatsuba-on-power-of-2-length k x y) ≤ 6 * k
  using f-bound[OF assms] f-linear[of k] by simp

end

```

```

function karatsuba-on-power-of-2-length-tm :: nat ⇒ nat-lsbf ⇒ nat-lsbf ⇒ nat-lsbf
tm where
karatsuba-on-power-of-2-length-tm k xs ys =1 do {
  b ← k ≤t karatsuba-lower-bound;
  (if b then grid-mul-nat-tm xs ys else do {
    (x0, x1) ← split-tm xs;
    (y0, y1) ← split-tm ys;
    k-div-2 ← k divt 2;
    prod0 ← karatsuba-on-power-of-2-length-tm k-div-2 x0 y0;
    prod1 ← karatsuba-on-power-of-2-length-tm k-div-2 x1 y1;
    abs-diff-x ← (abs-diff-tm x0 x1 ≫≡ fill-tm k-div-2);
    abs-diff-y ← (abs-diff-tm y0 y1 ≫≡ fill-tm k-div-2);
    prod2 ← karatsuba-on-power-of-2-length-tm k-div-2 abs-diff-x abs-diff-y;
    sgnx ← x1 ≤nt x0;
    sgny ← y1 ≤nt y0;
    sgnxy ← sgnx =t sgny;
    — construct return value
    add01 ← prod0 +nt prod1;
    r ← (if sgnxy then add01 -nt prod2 else add01 +nt prod2);
    sr ← r >>nt k-div-2;
    add0sr ← prod0 +nt sr;
    s1 ← prod1 >>nt k;
    add0sr +nt s1
  })
}
by pat-completeness simp
termination
by (relation Wellfounded.measure (λp. size (fst p))) simp-all

declare karatsuba-on-power-of-2-length-tm.simps[simp del]

lemma val-karatsuba-on-power-of-2-length-tm[simp, val-simp]:
assumes k = 2 ^ l
assumes length xs = k length ys = k
shows val (karatsuba-on-power-of-2-length-tm k xs ys) = karatsuba-on-power-of-2-length
k xs ys
using assms proof (induction k arbitrary: l xs ys rule: less-induct)
case (less k)
show ?case
proof (cases k ≤ karatsuba-lower-bound)
case True
then show ?thesis
unfolding karatsuba-on-power-of-2-length-tm.simps[of k xs ys]
karatsuba-on-power-of-2-length.simps[of k xs ys]
val-bind-tm val-less-eq-nat-tm val-simps val-grid-mul-nat-tm
by simp
next
case False
interpret r: karatsuba-context k l xs ys

```

```

    using less False by unfold-locales simp-all
  have val0: val (karatsuba-on-power-of-2-length-tm r.k-div-2 r.x0 r.y0) = r.prod0
    unfolding r.prod0-def
    by (intro less.IH[OF r.k-div-2-less-k r.k-div-2 r.length-x-split(1) r.length-y-split(1)])
  have val1: val (karatsuba-on-power-of-2-length-tm r.k-div-2 r.x1 r.y1) = r.prod1
    unfolding r.prod1-def
    by (intro less.IH[OF r.k-div-2-less-k r.k-div-2 r.length-x-split(2) r.length-y-split(2)])
  have val2: val (karatsuba-on-power-of-2-length-tm r.k-div-2 r.fill-abs-diff-x r.fill-abs-diff-y)
= r.prod2
    unfolding r.prod2-def r.fill-abs-diff-x-def[symmetric] r.fill-abs-diff-y-def[symmetric]
    apply (intro less.IH[OF r.k-div-2-less-k r.k-div-2])
    subgoal unfolding r.fill-abs-diff-x-def by (rule r.length-fill-abs-diff-x0-x1)
    subgoal unfolding r.fill-abs-diff-y-def by (rule r.length-fill-abs-diff-y0-y1)
    done
  have val (karatsuba-on-power-of-2-length-tm k xs ys) = r.add0sr +n r.s1
    unfolding karatsuba-on-power-of-2-length-tm.simps[of k xs ys]
    val-bind-tm val-less-eq-nat-tm val-simps val-split-tm r.split-x r.split-y
    val-divide-nat-tm val-abs-diff-tm val-fill-tm r.k-div-2-def[symmetric]
    val-compare-nat-tm val-subtract-nat-tm val-add-nat-tm val-equal-bool-tm val-shift-right-tm
    Let-def Product-Type.prod.case r.defs2[symmetric] r.defs3[symmetric] val0
val1 val2
    using False by argo
  also have ... = karatsuba-on-power-of-2-length k xs ys
    using r.recursive
    unfolding karatsuba-on-power-of-2-length.simps[of k xs ys]
    Let-def r.split-x r.split-y Product-Type.prod.case r.defs2[symmetric] r.defs3[symmetric]
by argo
  finally show ?thesis .
qed
qed

fun h where
h k = (if k ≤ karatsuba-lower-bound then 2 * k + 8 * k * k + 3
  else 407 + 224 * k + 3 * h (k div 2))
declare h.simps[simp del]

lemma time-karatsuba-on-power-of-2-length-tm-le-h:
  assumes k = 2 ^ l
  assumes length xs = k length ys = k
  shows time (karatsuba-on-power-of-2-length-tm k xs ys) ≤ h k
using assms proof (induction k arbitrary: xs ys l rule: less-induct)
  case (less k)
  show ?case
  proof (cases k ≤ karatsuba-lower-bound)
  case True
  then have time (karatsuba-on-power-of-2-length-tm k xs ys) ≤
    2 * k + 8 * length xs * max (length xs) (length ys) + 3
    unfolding karatsuba-on-power-of-2-length-tm.simps[of k xs ys]
    apply (simp add: time-less-eq-nat-tm)

```

```

    apply (subst Suc-eq-plus1)+
    apply (estimation estimate: time-grid-mul-nat-tm-le)
    apply (rule order.refl)
    done
  also have ... = 2 * k + 8 * k * k + 3 unfolding less(3) less(4) by simp
  finally show ?thesis unfolding h.simps[of k] using True by simp
next
case False
then interpret r: karatsuba-context k l xs ys
  by (unfold-locales; simp add: less)
have val0: val (karatsuba-on-power-of-2-length-tm r.k-div-2 r.x0 r.y0) = r.prod0
  unfolding r.prod0-def
  by (intro val-karatsuba-on-power-of-2-length-tm[OF r.k-div-2 r.length-x-split(1)]
r.length-y-split(1))
have val1: val (karatsuba-on-power-of-2-length-tm r.k-div-2 r.x1 r.y1) = r.prod1
  unfolding r.prod1-def
  by (intro val-karatsuba-on-power-of-2-length-tm[OF r.k-div-2 r.length-x-split(2)]
r.length-y-split(2))
have val2: val (karatsuba-on-power-of-2-length-tm r.k-div-2 r.fill-abs-diff-x r.fill-abs-diff-y)
= r.prod2
  unfolding r.prod2-def r.fill-abs-diff-x-def[symmetric] r.fill-abs-diff-y-def[symmetric]
  apply (intro val-karatsuba-on-power-of-2-length-tm[OF r.k-div-2])
  subgoal unfolding r.fill-abs-diff-x-def by (rule r.length-fill-abs-diff-x0-x1)
  subgoal unfolding r.fill-abs-diff-y-def by (rule r.length-fill-abs-diff-y0-y1)
  done

have len0: length (r.prod0) ≤ 3 * k
  unfolding r.prod0-def
  apply (estimation estimate: length-karatsuba-on-power-of-2-length[OF r.k-div-2
r.length-x-split(1) r.length-y-split(1)])
  unfolding r.k-div-2-def
  by simp
have len1: length (r.prod1) ≤ 3 * k
  unfolding r.prod1-def
  apply (estimation estimate: length-karatsuba-on-power-of-2-length[OF r.k-div-2
r.length-x-split(2) r.length-y-split(2)])
  unfolding r.k-div-2-def
  by simp
have len2: length (r.prod2) ≤ 3 * k
  unfolding r.prod2-def
  apply (estimation estimate: length-karatsuba-on-power-of-2-length[OF r.k-div-2
r.length-fill-abs-diff-x0-x1 r.length-fill-abs-diff-y0-y1])
  unfolding r.k-div-2-def
  by simp

have len01: length r.add01 ≤ 3 * k + 1
  unfolding r.add01-def
  apply (estimation estimate: length-add-nat-upper)
  apply (estimation estimate: len0)

```

```

    apply (estimation estimate: len1)
  by simp
have lenr: length r.r ≤ 3 * k + 2
  unfolding r.r-def if-distrib[of length]
  apply (estimation estimate: length-subtract-nat-le)
  apply (estimation estimate: length-add-nat-upper)
  apply (estimation estimate: len01)
  apply (estimation estimate: len2)
  by simp
have lensr: length r.sr ≤ r.k-div-2 + 3 * k + 2
  unfolding r.sr-def
  apply (subst length-shift-right)
  apply (estimation estimate: lenr)
  by simp
have len0sr: length r.add0sr ≤ r.k-div-2 + 3 * k + 3
  unfolding r.add0sr-def
  apply (estimation estimate: length-add-nat-upper)
  apply (estimation estimate: len0)
  apply (estimation estimate: lensr)
  by simp
have lens1: length r.s1 ≤ 4 * k
  unfolding r.s1-def
  apply (subst length-shift-right)
  apply (estimation estimate: len1)
  by simp

  have time0: time (karatsuba-on-power-of-2-length-tm r.k-div-2 r.x0 r.y0) ≤ h
r.k-div-2
  by (intro less.IH[OF r.k-div-2-less-k r.k-div-2 r.length-x-split(1) r.length-y-split(1)])
  have time1: time (karatsuba-on-power-of-2-length-tm r.k-div-2 r.x1 r.y1) ≤ h
r.k-div-2
  by (intro less.IH[OF r.k-div-2-less-k r.k-div-2 r.length-x-split(2) r.length-y-split(2)])
  have time2: time (karatsuba-on-power-of-2-length-tm r.k-div-2 r.fill-abs-diff-x
r.fill-abs-diff-y) ≤ h r.k-div-2
  apply (intro less.IH[OF r.k-div-2-less-k r.k-div-2])
  subgoal unfolding r.fill-abs-diff-x-def using r.length-fill-abs-diff-x0-x1 by
assumption
  subgoal unfolding r.fill-abs-diff-y-def using r.length-fill-abs-diff-y0-y1 by
assumption
  done

have time (karatsuba-on-power-of-2-length-tm k xs ys) =
  time (k ≤t karatsuba-lower-bound) +
  time (split-tm xs) +
  time (split-tm ys) +
  time (k divt 2) +
  time (karatsuba-on-power-of-2-length-tm r.k-div-2 r.x0 r.y0) +
  time (karatsuba-on-power-of-2-length-tm r.k-div-2 r.x1 r.y1) +
  time (abs-diff-tm r.x0 r.x1) + time (fill-tm r.k-div-2 (abs-diff r.x0 r.x1)) +

```

$time (abs\text{-}diff\text{-}tm\ r.y0\ r.y1) + time (fill\text{-}tm\ r.k\text{-}div\text{-}2\ (abs\text{-}diff\ r.y0\ r.y1)) +$
 $time (karatsuba\text{-}on\text{-}power\text{-}of\text{-}2\text{-}length\text{-}tm\ r.k\text{-}div\text{-}2\ r.fill\text{-}abs\text{-}diff\text{-}x\ r.fill\text{-}abs\text{-}diff\text{-}y)$
+
 $time (r.x1 \leq_{nt} r.x0) +$
 $time (r.y1 \leq_{nt} r.y0) +$
 $time (r.sgnx =_t r.sgny) +$
 $time (add\text{-}nat\text{-}tm\ r.prod0\ r.prod1) +$
 $(if\ r.sgnxy\ then\ time (r.add01\ -_{nt}\ r.prod2)$
 $\quad\quad\quad else\ time (r.add01\ +_{nt}\ r.prod2)) +$
 $time (r.r >>_{nt} r.k\text{-}div\text{-}2) +$
 $time (r.prod0 +_{nt} r.sr) +$
 $time (r.prod1 >>_{nt} k) +$
 $time (r.add0sr +_{nt} r.s1) + 1$
unfolding *karatsuba-on-power-of-2-length-tm.simps*[of *k xs ys*]
tm-time-simps if-distrib[of *time*] *val-less-eq-nat-tm val-split-tm r.defs1*
Product-Type.prod.case val-divide-nat-tm r.defs2[*symmetric*] *r.defs3*[*symmetric*]
val-abs-diff-tm val-simps val-fill-tm val-karatsuba-on-power-of-2-length-tm
val-compare-nat-tm Let-def val0 val1 val2 val-add-nat-tm val-equal-bool-tm
val-subtract-nat-tm
by (*auto simp: False r.defs2*[*symmetric*] *r.defs3*[*symmetric*])
also have $\dots \leq 2 * k + 2 +$
 $(10 * k + 16) + (10 * k + 16) +$
 $(8 * k + 11) +$
 $h (k\ div\ 2) +$
 $h (k\ div\ 2) +$
 $(31 * k + 100) +$
 $(2 * k + 5) +$
 $(31 * k + 100) +$
 $(2 * k + 5) +$
 $h (k\ div\ 2) +$
 $(7 * k + 23) +$
 $(7 * k + 23) +$
 $2 +$
 $(6 * k + 3) +$
 $(90 * k + 78) +$
 $(k + 3) +$
 $(7 * k + 7) +$
 $(2 * k + 3) +$
 $(8 * k + 9) +$
 1
apply (*intro add-mono*)
subgoal by (*estimation estimate: time-less-eq-nat-tm-le*) *simp*
subgoal by (*estimation estimate: time-split-tm-le*) (*simp add: less*)
subgoal by (*estimation estimate: time-split-tm-le*) (*simp add: less*)
subgoal by (*estimation estimate: time-divide-nat-tm-le*) *simp*
subgoal by (*estimation estimate: time0*) (*simp add: r.k-div-2-def*)
subgoal by (*estimation estimate: time1*) (*simp add: r.k-div-2-def*)
subgoal apply (*estimation estimate: time-abs-diff-tm-le*) **unfolding** *r.length-x-split*
r.k-div-2-def **by** *simp*


```

    subgoal apply (estimation estimate: time-fill-tm-le) using r.length-abs-diff-x0-x1
r.k-div-2-def by simp
    subgoal apply (estimation estimate: time-abs-diff-tm-le) unfolding r.length-y-split
r.k-div-2-def by simp
    subgoal apply (estimation estimate: time-fill-tm-le) using r.length-abs-diff-y0-y1
r.k-div-2-def by simp
    subgoal by (estimation estimate: time2) (simp add: r.k-div-2-def)
    subgoal apply (estimation estimate: time-compare-nat-tm-le) using r.length-x-split
r.k-div-2-def by simp
    subgoal apply (estimation estimate: time-compare-nat-tm-le) using r.length-y-split
r.k-div-2-def by simp
    subgoal using time-equal-bool-tm-le by simp
    subgoal
      apply (estimation estimate: time-add-nat-tm-le)
      apply (estimation estimate: len0)
      apply (estimation estimate: len1)
      by simp
    subgoal
      apply (estimation estimate: time-subtract-nat-tm-le)
      apply (estimation estimate: time-add-nat-tm-le)
      apply (estimation estimate: len01)
      apply (estimation estimate: len2)
      by simp
    subgoal using r.k-div-2-def by simp
    subgoal
      apply (estimation estimate: time-add-nat-tm-le)
      apply (estimation estimate: len0)
      apply (estimation estimate: lensr)
      using r.k-div-2-def by simp
    subgoal by simp
    subgoal
      apply (estimation estimate: time-add-nat-tm-le)
      apply (estimation estimate: len0sr)
      apply (estimation estimate: lens1)
      using r.k-div-2-less-k by presburger
    subgoal by simp
    done
  also have ... = 407 + 224 * k + 3 * h (k div 2)
    by simp
  finally show ?thesis unfolding h.simps[of k] using False by simp
qed
qed

```

```

lemma n-div-2: n div 2 = nat ⌊real n / 2⌋
  by linarith

```

```

function h-real :: nat ⇒ real where
x ≤ karatsuba-lower-bound ⇒ h-real x = 8 * x * x + 2 * x + 3
| x > karatsuba-lower-bound ⇒ h-real x = 407 + 224 * x + 3 * h-real (nat (⌊real

```

$x / 2]$)
by *force simp-all*
termination
by (*relation Wellfounded.measure* ($\lambda x. x$)) (*simp-all add: n-div-2[symmetric]*)

lemma *h-h-real*: $\text{real } (h\ k) = h\text{-real } k$
apply (*induction k rule: h.induct*)
subgoal for k
apply (*cases* $k \leq \text{karatsuba-lower-bound}$)
by (*simp-all add: h-real.simps[of k] h.simps[of k] n-div-2 del: h-real.simps*)
done

lemma *h-real-bigo*: $h\text{-real} \in O(\lambda n. \text{real } n \text{ powr } \log 2 3)$
by (*master-theorem 1 p': 1*) (*auto simp: powr-divide*)

definition *karatsuba-mul-nat-tm* :: $\text{nat-lsbf} \Rightarrow \text{nat-lsbf} \Rightarrow \text{nat-lsbf } tm$ **where**
karatsuba-mul-nat-tm $xs\ ys = 1$ **do** {
 $lenx \leftarrow \text{length-tm } xs$;
 $leny \leftarrow \text{length-tm } ys$;
 $k \leftarrow \text{max-nat-tm } lenx\ leny \gg \text{next-power-of-2-tm}$;
 $fillx \leftarrow \text{fill-tm } k\ xs$;
 $filly \leftarrow \text{fill-tm } k\ ys$;
 $\text{karatsuba-on-power-of-2-length-tm } k\ fillx\ filly$
}

lemma *val-karatsuba-mul-nat-tm*[*simp, val-simp*]: $\text{val } (\text{karatsuba-mul-nat-tm } xs\ ys)$
 $= \text{karatsuba-mul-nat } xs\ ys$

proof –

define k **where** $k = \text{next-power-of-2 } (\text{max } (\text{length } xs) (\text{length } ys))$
then obtain l **where** $k = 2 \wedge l$ **using** *next-power-of-2-is-power-of-2* **by** *auto*
have $\text{val } (\text{karatsuba-on-power-of-2-length-tm } k\ (\text{fill } k\ xs)\ (\text{fill } k\ ys)) =$
 $\text{karatsuba-on-power-of-2-length } k\ (\text{fill } k\ xs)\ (\text{fill } k\ ys)$
apply (*intro val-karatsuba-on-power-of-2-length-tm[OF ‹k = 2 ^ l›]*)
unfolding *k-def* **using** *next-power-of-2-lower-bound[of max (length xs) (length ys)]* **by** *auto*
then show *?thesis*
unfolding *karatsuba-mul-nat-tm-def karatsuba-mul-nat.simps val-simp Let-def k-def* .
qed

definition *time-karatsuba-mul-nat-bound* **where**

time-karatsuba-mul-nat-bound $m = 53 + 218 * (\text{next-power-of-2 } m) + h (\text{next-power-of-2 } m)$

The following two lemmas are one way to formally express the more informal statement "Karatsuba Multiplication needs $\mathcal{O}(n^{\log_2 3})$ bit operations for input numbers of length n ".

theorem *time-karatsuba-mul-nat-tm-le*:

assumes $\text{max } (\text{length } xs) (\text{length } ys) = m$

shows $\text{time}(\text{karatsuba-mul-nat-tm } xs \ ys) \leq \text{time-karatsuba-mul-nat-bound } m$
proof –
define k **where** $k = \text{next-power-of-2 } m$
then obtain l **where** $k = 2 \wedge l$ **using** $\text{next-power-of-2-is-power-of-2}$ **by** auto
have $\text{lens: length } xs \leq k \ \text{length } ys \leq k$
using $\text{assms next-power-of-2-lower-bound[of } m] \ k\text{-def}$ **by** simp-all
have $\text{time}(\text{karatsuba-mul-nat-tm } xs \ ys) =$
 $\text{time}(\text{length-tm } xs) +$
 $\text{time}(\text{length-tm } ys) +$
 $\text{time}(\text{max-nat-tm }(\text{length } xs) \ (\text{length } ys)) +$
 $\text{time}(\text{next-power-of-2-tm }(\text{max }(\text{length } xs) \ (\text{length } ys))) +$
 $\text{time}(\text{fill-tm } k \ xs) +$
 $\text{time}(\text{fill-tm } k \ ys) +$
 $\text{time}(\text{karatsuba-on-power-of-2-length-tm } k \ (\text{fill } k \ xs) \ (\text{fill } k \ ys)) + 1$
unfolding $\text{karatsuba-mul-nat-tm-def}$ tm-time-simps val-simp Let-def
 $\text{assms } k\text{-def[symmetric]}$ **by** presburger
also have $\dots \leq$
 $(k + 1) + (k + 1) + (2 * k + 3) +$
 $(208 * k + 37) +$
 $(3 * k + 5) +$
 $(3 * k + 5) +$
 $h \ k +$
 1
apply $(\text{intro add-mono order.refl})$
subgoal by (simp add: lens)
subgoal by (simp add: lens)
subgoal apply $(\text{estimation estimate: time-max-nat-tm-le})$ **using** lens **by** simp
subgoal apply $(\text{estimation estimate: time-next-power-of-2-tm-le})$ **using** lens
by simp
subgoal apply $(\text{estimation estimate: time-fill-tm-le})$ **using** lens **by** simp
subgoal apply $(\text{estimation estimate: time-fill-tm-le})$ **using** lens **by** simp
subgoal apply $(\text{intro time-karatsuba-on-power-of-2-length-tm-le-h}[OF \ \langle k = 2$
 $\wedge l \rangle])$ **using** lens
by auto
done
also have $\dots = 53 + 218 * k + h \ k$ **by** simp
finally show $\text{?thesis unfolding } k\text{-def time-karatsuba-mul-nat-bound-def[symmetric]}$
 \cdot
qed

theorem $\text{time-karatsuba-mul-nat-bound-bigo: time-karatsuba-mul-nat-bound} \in O(\lambda m. m \ \text{powr } \log 2 \ 3)$

proof –
define t **where** $t = (\lambda m. \text{real } (53 + 218 * m + h \ m))$
then have $\text{time-karatsuba-mul-nat-bound} = t \circ \text{next-power-of-2}$
unfolding $\text{time-karatsuba-mul-nat-bound-def}$ **by** auto
also have $\dots \in O(\lambda m. m \ \text{powr } \log 2 \ 3)$
apply $(\text{intro powr-bigo-linear-index-transformation})$
subgoal

```

proof –
  have ( $\lambda x. \text{real } (\text{next-power-of-2 } x) \in O(\lambda x. \text{real } (2 * x + 1))$ )
    apply (intro landau-mono-always)
    using next-power-of-2-upper-bound' real-mono by simp-all
  moreover have ( $\lambda x. \text{real } (2 * x + 1) \in O(\text{real})$ ) by auto
  ultimately show ( $\lambda x. \text{real } (\text{next-power-of-2 } x) \in O(\text{real})$ )
    using landau-o.big.trans by blast
qed
subgoal unfolding t-def real-linear real-multiplicative h-h-real
apply (intro sum-in-bigo)
subgoal by auto
subgoal by auto
subgoal using h-real-bigo .
done
subgoal by auto
done
finally show ?thesis .
qed

end

```

13 Code Generation

```

theory Karatsuba-Code-Nat
  imports Main HOL-Library.Code-Binary-Nat Karatsuba
begin

```

In this theory, the Karatsuba Multiplication implemented in *Karatsuba* is used for code generation. This is not really practical (except beginning at 3000 decimal digits), but merely a nice gimmick.

```

fun from-numeral :: num  $\Rightarrow$  nat-lsbf where
  from-numeral num.One = [True]
| from-numeral (num.Bit0 x) = False # from-numeral x
| from-numeral (num.Bit1 x) = True # from-numeral x

```

```

lemma from-numeral-nonempty: from-numeral x  $\neq$  []
by (induction x rule: from-numeral.induct; simp)

```

```

lemma from-numeral-truncated: truncated (from-numeral x)
unfolding truncated-iff
by (induction x rule: from-numeral.induct; simp add: from-numeral-nonempty)

```

```

lemma to-nat-from-numeral-neq-zero: to-nat (from-numeral x)  $\neq$  0
using to-nat-zero-iff from-numeral-truncated from-numeral-nonempty by simp

```

```

fun to-numeral-of-truncated :: nat-lsbf  $\Rightarrow$  num where
to-numeral-of-truncated [] = num.One
| to-numeral-of-truncated [True] = num.One

```

| *to-numeral-of-truncated* (True # *xs*) = *num.Bit1* (*to-numeral-of-truncated xs*)
| *to-numeral-of-truncated* (False # *xs*) = *num.Bit0* (*to-numeral-of-truncated xs*)

lemma *to-numeral-of-truncated-from-numeral*:
to-numeral-of-truncated (*from-numeral x*) = *x*
apply (*induction x*)
subgoal by *simp*
subgoal by *simp*
subgoal for *x* **by** (*cases from-numeral x; simp*)
done

lemma *nat-of-num-to-numeral-of-truncated*:
assumes *truncated xs*
assumes *xs* ≠ []
shows *nat-of-num* (*to-numeral-of-truncated xs*) = *to-nat xs*
using *assms* **proof** (*induction xs* *rule: to-numeral-of-truncated.induct*)
case 1
then show ?*case* **by** *blast*
next
case 2
then show ?*case* **by** *simp*
next
case (3 *v va*)
note *truncated-Cons-imp-truncated-tl*[*OF* 3.*prems*(1)]
from 3.*IH*[*OF* *this*] **show** ?*case* **by** *simp*
next
case (4 *xs*)
from 4.*prems*(1) **have** *xs* ≠ []
apply (*intro ccontr*[*of xs* ≠ []])
by (*simp add: truncated-iff*)
note *truncated-Cons-imp-truncated-tl*[*OF* 4.*prems*(1)]
from 4.*IH*[*OF* *this* <*xs* ≠ []>] **show** ?*case* **by** *simp*
qed

definition *to-numeral* :: *nat-lsbf* ⇒ *num* **where**
to-numeral xs = (*let xs'* = *Nat-LSBF.truncate xs* *in to-numeral-of-truncated xs'*)

lemma *to-numeral-from-numeral*: *to-numeral* (*from-numeral x*) = *x*
unfolding *to-numeral-def* *Let-def*
using *from-numeral-truncated to-numeral-of-truncated-from-numeral*
by *simp*

lemma *nat-of-num-to-numeral*:
assumes *to-nat xs* ≠ 0
shows *nat-of-num* (*to-numeral xs*) = *to-nat xs*
unfolding *to-numeral-def* *Let-def*
using *assms* *nat-of-num-to-numeral-of-truncated*[*of truncate xs, OF truncate-truncate*]
unfolding *nat-lsbf.to-f-elem*
using *to-nat-zero-iff*

```

by simp

lemma l0:
  assumes truncated xs
  shows to-numeral-of-truncated xs = num-of-nat (to-nat xs)
  using assms
  by (metis nat-of-num-inverse nat-of-num-to-numeral-of-truncated num-of-nat.simps(1)
to-nat.simps(1) to-numeral-of-truncated.simps(1))

lemma l1: to-numeral xs = num-of-nat (to-nat xs)
  unfolding to-numeral-def Let-def
  using l0[of truncate xs] truncate-truncate[of xs] nat-lsbf.to-f-elem
  by simp

lemma l2: to-nat (from-numeral x) = nat-of-num x
  by (metis nat-of-num-to-numeral to-nat-from-numeral-neq-zero to-numeral-from-numeral)

lemma[code]:
  (x::num) * y = to-numeral (karatsuba-mul-nat (from-numeral x) (from-numeral
y))
  unfolding l1 karatsuba-mul-nat-correct l2 times-num-def by (rule refl)

end

```

References

- [1] A. Karatsuba and Y. Ofman. Multiplication of many-digital numbers by automatic computers. *Dokl. Akad. Nauk SSSR*, 145:293–294, 1962. <http://mi.mathnet.ru/dan26729>.
- [2] T. Nipkow. Verified root-balanced trees. In B.-Y. E. Chang, editor, *Asian Symposium on Programming Languages and Systems, APLAS 2017*, volume 10695 of *LNCS*, pages 255–272. Springer, 2017. <https://www21.in.tum.de/~nipkow/pubs/aplas17.pdf>.