

# Depth-First Search

Toshiaki Nishihara      Yasuhiko Minamide

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## Abstract

Depth-first search of a graph is formalized with `function`. It is shown that it visits all of the reachable nodes from a given list of nodes. Executable ML code of depth-first search is obtained with code generation feature of Isabelle/HOL. The formalization contains two implementations of depth-first search: one by stack and one by nested recursion. They are shown to be equivalent. The termination condition of the version with nested-recursion is shown by the method of inductive invariants.

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## 1 Depth-First Search

```
theory DFS
imports Main
begin
```

### 1.1 Definition of Graphs

```
typedcl node
type-synonym graph = (node * node) list

primrec nexts :: [graph, node] ⇒ node list
where
  nexts [] n = []
| nexts (e#es) n = (if fst e = n then snd e # nexts es n else nexts es n)
```

**definition** *nextss* :: [graph, node list]  $\Rightarrow$  node set  
 where *nextss* *g xs* = set *g* “ set *xs*

**lemma** *nexts-set*:  $y \in \text{set } (\text{nexts } g \ x) = ((x,y) \in \text{set } g)$   
 by (induct *g*) auto

**lemma** *nextss-Cons*:  $\text{nextss } g \ (x\#xs) = \text{set } (\text{nexts } g \ x) \cup \text{nextss } g \ xs$   
 unfolding *nextss-def* by (auto simp add:Image-def *nexts-set*)

**definition** *reachable* :: [graph, node list]  $\Rightarrow$  node set  
 where *reachable* *g xs* = (set *g*)<sup>\*</sup> “ set *xs*

## 1.2 Depth-First Search with Stack

**definition** *nodes-of* :: graph  $\Rightarrow$  node set  
 where *nodes-of* *g* = set (map fst *g* @ map snd *g*)

**lemma** [*simp*]:  $x \notin \text{nodes-of } g \Longrightarrow \text{nexts } g \ x = []$   
 by (induct *g*) (auto simp add: *nodes-of-def*)

**lemma** [*simp*]: finite (*nodes-of* *g* - set *ys*)

**proof**(rule *finite-subset*)  
 show finite (*nodes-of* *g*)  
 by (auto simp add: *nodes-of-def*)  
**qed** (auto)

**function**

*dfs* :: graph  $\Rightarrow$  node list  $\Rightarrow$  node list  $\Rightarrow$  node list  
 where  
   *dfs-base*: *dfs* *g* [] *ys* = *ys*  
 | *dfs-inductive*: *dfs* *g* (*x*\#*xs*) *ys* = (if List.member *ys* *x* then *dfs* *g* *xs* *ys*  
                                   else *dfs* *g* (*nexts* *g* *x*@*xs*) (*x*\#*ys*))  
 by *pat-completeness* auto

**termination**

**apply** (relation *inv-image* (*finite-psubset* <\*lex\*> *less-than*)  
           ( $\lambda(g,xs,ys). (\text{nodes-of } g - \text{set } ys, \text{size } xs)$ ))

**apply** *auto*[1]

**apply** (*simp-all* add: *finite-psubset-def*)

**by** (*case-tac*  $x \in \text{nodes-of } g$ ) (auto simp add: *List.member-def*)

- The second argument of *dfs* is a stack of nodes that will be visited.
- The third argument of *dfs* is a list of nodes that have been visited already.

### 1.3 Depth-First Search with Nested-Recursion

**function**

$dfs2 :: graph \Rightarrow node\ list \Rightarrow node\ list \Rightarrow node\ list$

**where**

$dfs2\ g\ []\ ys = ys$

|  $dfs2$ -inductive:

$dfs2\ g\ (x\#\!xs)\ ys = (if\ List.member\ ys\ x\ then\ dfs2\ g\ xs\ ys$   
 $else\ dfs2\ g\ xs\ (dfs2\ g\ (nexts\ g\ x)\ (x\#\!ys)))$

**by**  $pat$ -completeness  $auto$

**lemma**  $dfs2$ -invariant:  $dfs2$ -dom  $(g, xs, ys) \implies set\ ys \subseteq set\ (dfs2\ g\ xs\ ys)$

**by** (induct  $g\ xs\ ys$  rule:  $dfs2$ .pinduct) (force simp add:  $dfs2$ .psimps)+

**termination**  $dfs2$

**apply** (relation  $inv$ -image (finite-psubset  $\langle *lex* \rangle$  less-than)

$(\lambda(g,xs,ys). (nodes-of\ g - set\ ys, size\ xs)))$ )

**apply**  $auto$ [1]

**apply** (simp-all add: finite-psubset-def)

**apply** (case-tac  $x \in nodes-of\ g$ )

**apply** (auto simp add: List.member-def)[2]

**by** (insert  $dfs2$ -invariant) force

**lemma**  $dfs$ -app:  $dfs\ g\ (xs@ys)\ zs = dfs\ g\ ys\ (dfs\ g\ xs\ zs)$

**by** (induct  $g\ xs\ zs$  rule:  $dfs$ .induct)  $auto$

**lemma**  $dfs2\ g\ xs\ ys = dfs\ g\ xs\ ys$

**by** (induct  $g\ xs\ ys$  rule:  $dfs2$ .induct) (auto simp add:  $dfs$ -app)

### 1.4 Basic Properties

**lemma**  $visit$ -subset- $dfs$ :  $set\ ys \subseteq set\ (dfs\ g\ xs\ ys)$

**by** (induct  $g\ xs\ ys$  rule:  $dfs$ .induct)  $auto$

**lemma**  $next$ -subset- $dfs$ :  $set\ xs \subseteq set\ (dfs\ g\ xs\ ys)$

**proof**(induct  $g\ xs\ ys$  rule: $dfs$ .induct)

**case**(2  $g\ x\ xs\ ys$ )

**show** ?case

**proof**(cases  $x \in set\ ys$ )

**case** True

**have**  $set\ ys \subseteq set\ (dfs\ g\ xs\ ys)$

**by** (rule  $visit$ -subset- $dfs$ )

**with** 2 **and** True **show** ?thesis

**by** (auto simp add: List.member-def)

**next**

**case** False

**have**  $set\ (x\#\!ys) \subseteq set\ (dfs\ g\ (nexts\ g\ x\ @\ xs)\ (x\#\!ys))$

**by**(rule  $visit$ -subset- $dfs$ )

**with** 2 **and** *False* **show** *?thesis*  
**by** (*auto simp add: List.member-def*)  
**qed**  
**qed**(*simp*)

**lemma** *nextss-closed-dfs'*[*rule-format*]:  
 $nextss\ g\ ys \subseteq set\ xs \cup set\ ys \longrightarrow nextss\ g\ (dfs\ g\ xs\ ys) \subseteq set\ (dfs\ g\ xs\ ys)$   
**by** (*induct g xs ys rule:dfs.induct, auto simp add:nextss-Cons List.member-def*)

**lemma** *nextss-closed-dfs*:  $nextss\ g\ (dfs\ g\ xs\ []) \subseteq set\ (dfs\ g\ xs\ [])$   
**by** (*rule nextss-closed-dfs', simp add: nextss-def*)

**lemma** *Image-closed-trancl*: **assumes**  $r\ \text{“}\ X \subseteq X\ \text{”}$  **shows**  $r^*\ \text{“}\ X = X\ \text{”}$   
**proof**  
**show**  $r^*\ \text{“}\ X \subseteq X\ \text{”}$   
**proof** –  
{  
  **fix**  $x\ y$   
  **assume**  $y: y \in X$   
  **assume**  $(y,x) \in r^*$   
  **then have**  $x \in X$   
  **by** (*induct*) (*insert assms y, auto simp add: Image-def*)  
}  
**then show** *?thesis* **unfolding** *Image-def* **by** *auto*  
**qed**  
**qed** *auto*

**lemma** *reachable-closed-dfs*:  $reachable\ g\ xs \subseteq set(dfs\ g\ xs\ [])$   
**proof** –  
  **have**  $reachable\ g\ xs \subseteq reachable\ g\ (dfs\ g\ xs\ [])$   
  **unfolding** *reachable-def* **by** (*rule Image-mono*) (*auto simp add: next-subset-dfs*)  
  **also have**  $\dots = set(dfs\ g\ xs\ [])$   
  **unfolding** *reachable-def*  
  **proof** (*rule Image-closed-trancl*)  
  **from** *nextss-closed-dfs*  
  **show**  $set\ g\ \text{“}\ set\ (dfs\ g\ xs\ []) \subseteq set\ (dfs\ g\ xs\ [])\ \text{”}$   
  **by** (*simp add: nextss-def*)  
**qed**  
  **finally show** *?thesis* .  
**qed**

**lemma** *reachable-nexts*:  $reachable\ g\ (nexts\ g\ x) \subseteq reachable\ g\ [x]$   
**unfolding** *reachable-def*  
**by** (*auto intro: converse-rtrancl-into-rtrancl simp: nexts-set*)

**lemma** *reachable-append*:  $reachable\ g\ (xs\ @\ ys) = reachable\ g\ xs \cup reachable\ g\ ys$   
**unfolding** *reachable-def* **by** *auto*

```

lemma dfs-subset-reachable-visit-nodes:  $set (dfs\ g\ xs\ ys) \subseteq reachable\ g\ xs \cup set\ ys$ 
proof(induct\ g\ xs\ ys\ rule: dfs.induct)
  case 1
  then show ?case by simp
next
  case (2 g\ x\ xs\ ys)
  show ?case
  proof (cases\ x \in set\ ys)
    case True
    with 2 show  $set (dfs\ g\ (x\#\!xs)\ ys) \subseteq reachable\ g\ (x\#\!xs) \cup set\ ys$ 
    by (auto\ simp\ add: reachable-def List.member-def)
  next
  case False
  have  $reachable\ g\ (nexts\ g\ x) \subseteq reachable\ g\ [x]$ 
  by (rule\ reachable-nexts)
  hence a:  $reachable\ g\ (nexts\ g\ x\ @\ xs) \subseteq reachable\ g\ (x\#\!xs)$ 
  by(simp\ add: reachable-append, auto\ simp\ add: reachable-def)
  with False 2
  show  $set (dfs\ g\ (x\#\!xs)\ ys) \subseteq reachable\ g\ (x\#\!xs) \cup set\ ys$ 
  by (auto\ simp\ add: reachable-def List.member-def)
  qed
qed

```

## 1.5 Correctness

```

theorem dfs-eq-reachable:  $set (dfs\ g\ xs\ []) = reachable\ g\ xs$ 
proof
  have  $set (dfs\ g\ xs\ []) \subseteq reachable\ g\ xs \cup set\ []$ 
  by (rule\ dfs-subset-reachable-visit-nodes[of\ g\ xs\ []])
  thus  $set (dfs\ g\ xs\ []) \subseteq reachable\ g\ xs$ 
  by simp
qed(rule\ reachable-closed-dfs)

```

```

theorem  $y \in set (dfs\ g\ [x]\ []) = ((x,y) \in (set\ g)^*)$ 
by(simp\ only:dfs-eq-reachable reachable-def, auto)

```

## 1.6 Executable Code

```

consts Node :: int  $\Rightarrow$  node

```

```

code-datatype Node

```

```

instantiation node :: equal
begin

```

```

definition equal-node :: node  $\Rightarrow$  node  $\Rightarrow$  bool
where
  [code del]: equal-node = HOL.eq

```

```
instance proof
qed (simp add: equal-node-def)

end

declare [[code abort: HOL.equal :: node ⇒ node ⇒ bool]]

export-code dfs dfs2 in SML file dfs.ML

end
```