



Verification in HOL of an algorithm for computing SCCs

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① Introduction

Definition

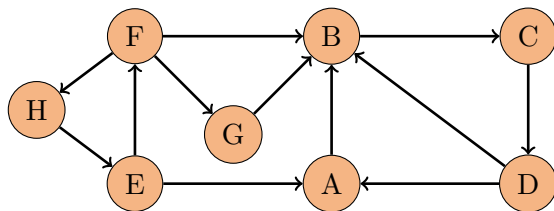
Motivation

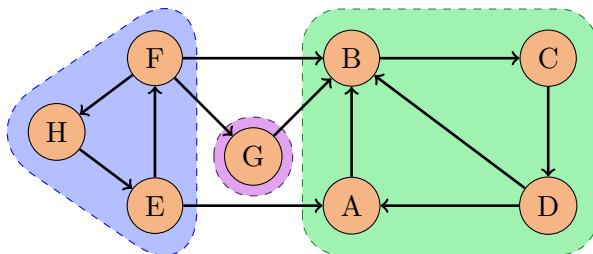
② Example of the proof process

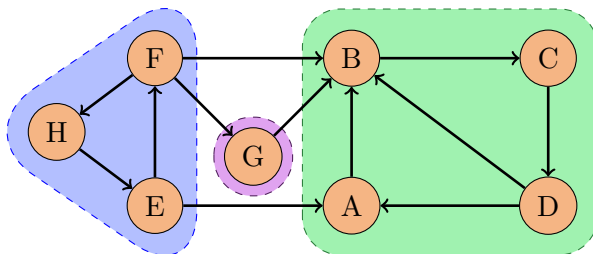
③ A sequential set-based SCC algorithm

Description of the algorithm

Implementation in Isabelle



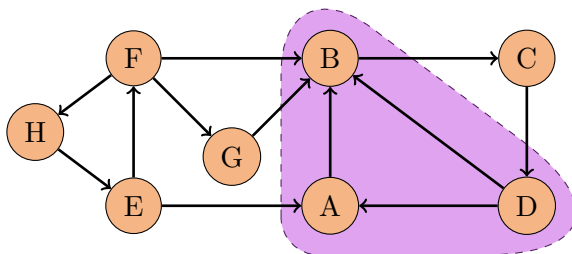




Definition 1

Let $\mathcal{G} := (\mathcal{V}, \mathcal{E})$ be a **directed graph** and $\mathcal{C} \subseteq \mathcal{V}$. \mathcal{C} is a SCC of \mathcal{G} if:

$$\forall x, y \in \mathcal{C}, (x \Rightarrow y) \wedge (y \Rightarrow x)$$



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$$\forall x, y \in \mathcal{C}, (x \Rightarrow y) \wedge (y \Rightarrow x)$$

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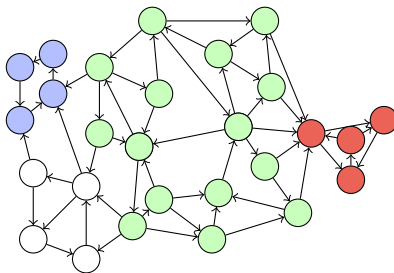
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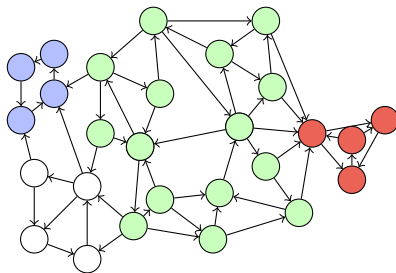
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Implementation in Isabelle



- Networks: connection and data sharing
- Model checking: counter-examples finding



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- Model checking: counter-examples finding

Efficient algorithms (ex: Tarjan)

- Formal verification of correctness is worthwhile
- Parallelization is another challenge

Isabelle / HOL

- Generic proof assistant
- Formalisation of mathematical proofs
- Higher-Order Logic theorem proving environment
- Powerful proof tools and language (Isar)
- Mutual induction, recursion and datatypes, complex pattern matching

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(Type definition)

```
datatype 'a list = Empty | Cons 'a "'a list"
```

- Generic / polymorphic and static type
- Implicit constructor definition
- Recursive structure giving an induction principle for that type

(Function definition)

```
fun concat :: "'a list  $\Rightarrow$  'a list  $\Rightarrow$  'a list" where  
  "concat Empty xs = xs"  
| "concat (Cons x xs) ys = Cons x (concat xs ys)"
```

```
fun rev :: "'a list  $\Rightarrow$  'a list" where  
  "rev Empty = Empty"  
| "rev (Cons x xs) = concat (rev xs) (Cons x Empty)"
```

(Theorem statement)

```
theorem rev_rev [simp]: "rev (rev x) = x"
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  apply (induction x)  
  apply auto
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(Subgoal)

```
⋀ x1 x.  
  rev (rev x) = x  $\implies$   
  rev (concat (rev x) (Cons x1 Empty)) = Cons x1 x
```


(Adding a first lemma)

```
lemma rev_concat [simp]:  
  "rev (concat xs ys) = concat (rev ys) (rev xs)"  
  apply (induction xs)  
  apply auto
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lemma rev_concat [simp]:  
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(Subgoals)

1. $\text{rev } ys = \text{concat } (\text{rev } ys) \text{ Empty}$
2. $\bigwedge x1 \ xs.$
 $\text{rev } (\text{concat } xs \ ys) = \text{concat } (\text{rev } ys) (\text{rev } xs) \implies$
 $\text{rev } (\text{concat } (\text{Cons } x1 \ xs) \ ys) = \text{concat } (\text{rev } ys) (\text{rev } (\text{Cons } x1 \ xs))$

(Adding a second lemma)

```
lemma concat_empty [simp]: "concat xs Empty = xs"  
  apply (induction xs)  
  apply auto
```

(Adding a third lemma: associative property)

```
lemma concat_assoc [simp]: "concat (concat xs ys) zs =  
concat xs (concat ys zs)"  
  apply (induction xs)  
  apply auto
```

```
theorem rev_rev [simp]: "rev (rev x) = x"  
  apply (induction x)  
  apply auto
```

No subgoals!

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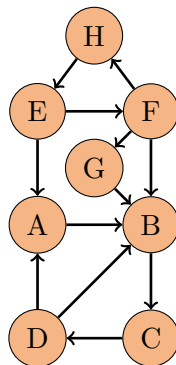
Implementation in Isabelle

Data: A graph $\mathcal{G} = (\mathcal{V}, \mathcal{E})$, a starting node v_0 ;

```

1 Initialize an empty set DEAD;
2 Initialize an empty set VISITED;
3 Initialize an empty stack R;
4 setBased( $v_0$ );
5 function setBased:  $v \in \mathcal{V} \rightarrow \text{None}$ 
6     VISITED := VISITED  $\cup \{v\}$ ;
7     R.push( $v$ );
8     foreach  $w \in \text{POST}(v)$  do
9         if  $w \in \text{DEAD}$  then
10             continue;
11         else if  $w \notin \text{VISITED}$  then
12             setBased( $w$ );
13         else
14             while  $\mathcal{S}(v) \neq \mathcal{S}(w)$  do
15                  $r := \text{R.pop}()$ ;
16                 UNITE( $\mathcal{S}, r, \text{R.top}()$ );
17     if  $v = \text{R.top}()$  then
18         report SCC  $\mathcal{S}(v)$ ;
19         DEAD := DEAD  $\cup \mathcal{S}(v)$ ;
20         R.pop();

```



$$R = \{\}$$

$$\text{VISITED} = \{\}$$

$$\text{DEAD} = \{\}$$

$$\mathcal{S} = \{A\} \cup \{B\} \cup \{C\} \cup \{D\} \cup \{E\} \cup \{F\} \cup \{G\} \cup \{H\}$$

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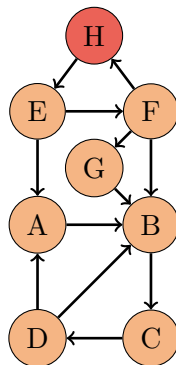
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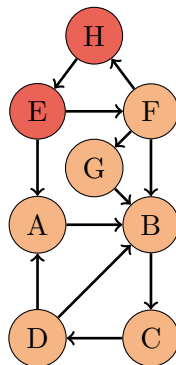
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VISITED := VISITED $\cup \{v\}$;

R.push(v);

foreach $w \in \text{POST}(v)$ **do**

if $w \in \text{DEAD}$ **then**

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else if $w \notin \text{VISITED}$ **then**

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else

while $S(v) \neq S(w)$ **do**

$r := \text{R.pop}()$;

 UNITE($S, r, \text{R.top}()$);

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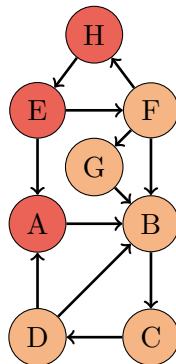
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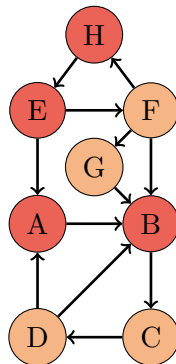
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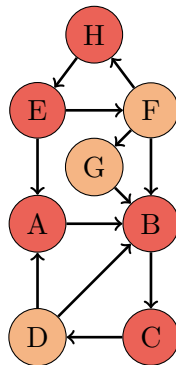
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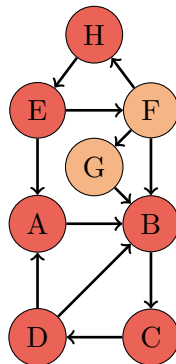
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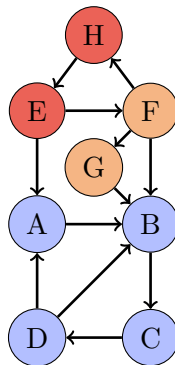
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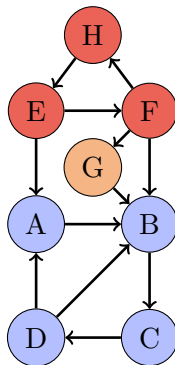
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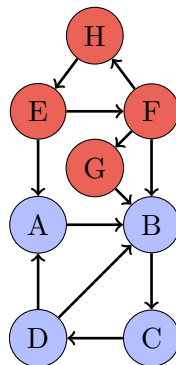
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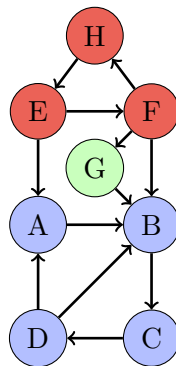
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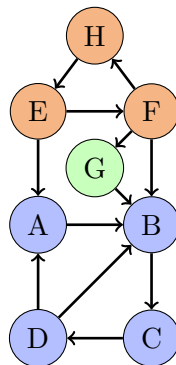
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```



$$R = \{\}$$

$$\text{VISITED} = \{H, E, A, B, C, D, F, G\}$$

$$\text{DEAD} = \{A, B, C, D, G, E, F, H\}$$

$$\mathcal{S} = \{A, B, C, D\} \cup \{E, F, H\} \cup \{G\}$$

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Description of the algorithm

Implementation in Isabelle

(Finite directed graphs)

```

locale graph =
  fixes vertices :: "'v set"
  and successors :: "'v ⇒ 'v set"
  assumes vfin: "finite vertices"
  and sclosed: "∀ x ∈ vertices. successors x ⊆ vertices"

```

```

abbreviation edge where
  "edge x y ≡ y ∈ successors x"

```

```

inductive reachable where
  reachable_refl[iff]: "reachable x x"
| reachable_succ[elim]:
  "[[edge x y; reachable y z]] ⇒ reachable x z"

```

(Finite directed graphs)

```
locale graph =  
  fixes vertices :: "'v set"  
  and successors :: "'v ⇒ 'v set"  
  assumes vfin: "finite vertices"  
  and sclosed: " $\forall x \in \text{vertices}. \text{successors } x \subseteq \text{vertices}$ "
```

```
abbreviation edge where  
"edge x y  $\equiv$  y  $\in$  successors x"
```

```
inductive reachable where  
  reachable_refl[iff]: "reachable x x"  
| reachable_succ[elim]:  
  "[edge x y; reachable y z]  $\implies$  reachable x z"
```

(SCC)

```
definition is_subscs where
```

```
"is_subscs S  $\equiv$   $\forall x \in S. \forall y \in S. \text{reachable } x y$ "
```

(Maximal SCC)

```
definition is_scc where
```

```
"is_scc S  $\equiv$  S  $\neq$  {}
```

```
 $\wedge$  is_subscs S
```

```
 $\wedge$  ( $\forall S'. S \subseteq S' \wedge \text{is\_subscs } S' \longrightarrow S' = S$ )"
```

Proof process

(Well-formed environment)

definition wf_env **where**

"wf_env e \equiv "

distinct (stack e)

\wedge set (stack e) \subseteq visited e

\wedge explored e \subseteq visited e

\wedge explored e \cap set (stack e) = $\{\}$

\wedge ($\forall v w. w \in \mathcal{S} e v \longleftrightarrow \mathcal{S} e v = \mathcal{S} e w$)

\wedge ($\forall v \in \text{set}(\text{stack } e). \forall w \in \text{set}(\text{stack } e). v \neq w \longrightarrow$
 $\mathcal{S} e v \cap \mathcal{S} e w = \{\}$)

\wedge ($\forall v. v \notin \text{visited } e \longrightarrow \mathcal{S} e v = \{v\}$)

$\wedge \bigcup \{\mathcal{S} e v \mid v. v \in \text{set}(\text{stack } e)\} = \text{visited } e - \text{explored } e$

```
definition pre_dfs where
  "pre_dfs v e  $\equiv$  wf_env e  $\wedge$  v  $\notin$  visited e"
definition post_dfs where "post_dfs v e  $\equiv$  wf_env e"
```

```
definition pre_dfss where "pre_dfs v vs e  $\equiv$  wf_env e"
definition post_dfss where "post_dfs v vs e  $\equiv$  wf_env e"
```



```
lemma pre_dfs_pre_dfss:  
  assumes "pre_dfs v e"  
  shows "pre_dfss v (successors v) (e(|visited:=visited e  $\cup$  {v},  
stack:= v # stack e|))"
```

```
lemma pre_dfss_pre_dfs:  
  fixes w  
  assumes "pre_dfss v vs e" and "w  $\notin$  visited e"  
  shows "pre_dfs w e"
```

```
lemma pre_dfs_implies_post_dfs:...
```

```
lemma pre_dfss_implies_post_dfss:...
```

Possible prospects

- Finish the entire proof (with termination and functions domains)
- Parallel algorithm for computing SCC ? Proof ?