Formal verification of an algorithm for computing strongly connected components

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Contents

1 Introduction

1.1 Academic context

This research work was carried out as part of my curriculum at the French École des Mines de Nancy. All documents such as codes or source papers are available on a GitHub repository.

1.2 Formal methods

Formal methods are a field of computer science related to mathematical logic and reasoning. The whole purpose of the discipline is to ensure by a logical proof that a given algorithm is not only correct on its domain of definition, but also to find – or define – that domain. Formal methods find applications in a variety of fields, both concrete, such as the railway industry or self-driving cars, and abstract, such as computational architecture.

Although a formal proof lies first on paper, the real formalisation starts when proofs are mechanised in a proof assistant.

sm: First, a stylistic remark: do not end lines in a LaTeX document using \\ (except in `tabular` environments or similar). Use a blank line to start a new paragraph: the style will define the appearance of a paragraph break.
More importantly, formal methods should not be equated with theorem proving. They are really about giving precise, mathematical definitions to computer science concepts. Although the purpose of giving such definitions is to enable formal verification, many techniques besides theorem proving, such as model-based testing, run-time monitoring, model checking etc. are used.

1.3 Isabelle (HOL)

Isabelle is a generic proof assistant. It allows mathematical formulas to be expressed in a formal language and provides tools for proving those formulas in a logical calculus.

isabelle.in.tum.de

Isabelle is a really powerful proof assistant coming with a higher order logic (HOL) proving environment. Isabelle proofs are written in the Isar ("intelligible semi-automated reasoning") language that is designed to make proofs readable and comprehensible for a mathematically inclined reader, with minimal overhead introduced by the formalism. In fact, "assistant" refers to the fact that the machine checks the proof provided by the user, in contrast to automatic theorem proving where the machine finds the proof itself. The tools for automation are intended to help the user write the proof at a conveniently high level, without needing to work at the level of a logical calculus, for example.

2 Formalisation

2.1 Strongly connected components

2.1.1 Directed graphs

Definition 1 (Reachability)**.** For two vertices x and y of $\mathcal{V}$, the reachability relation is noted "$\Rightarrow^*$" such that $x \Rightarrow^* y$ iff x can reach y in $\mathcal{G}$.

Remark 1. The relation $\Rightarrow^*$ is in fact the transitive closure of the binary relation $\Rightarrow$ defining edges in a graph.

Definition 2 (SCC)**.** Let $\mathcal{G} = (\mathcal{V} , \mathcal{E})$ be an directed graph. $\mathcal{C} \subseteq \mathcal{V}$ is a strongly connected component (SCC) of $\mathcal{G}$ if:

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

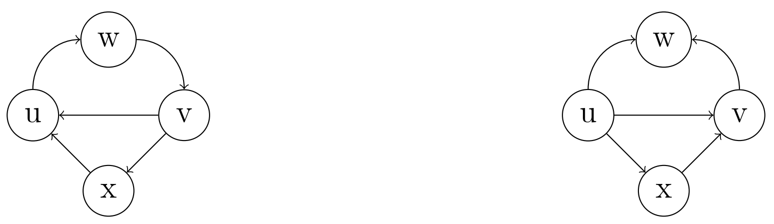
i.e. there is a path between every x and y in $\mathcal{C}$.

$\mathcal{C}$ is maximal, or $\mathcal{C}$ is a maximal SCC of $\mathcal{G}$ if there is no other SCC containing $\mathcal{C}$, *i.e.* if:

$$\forall \mathcal{X}, (\mathcal{C} \subseteq \mathcal{X}) \wedge (\forall x, y \in \mathcal{X}, (x \Rightarrow^* y) \wedge (y \Rightarrow^* x)) \implies \mathcal{C} = \mathcal{X}$$

Definition 3. (Strong connectedness) Let $\mathcal{G} = (\mathcal{V} , \mathcal{E})$ be a directed graph. $\mathcal{G}$ is strongly connected if $\mathcal{V}$ is a SCC.

2.1.2 Examples



(a) Strongly connected graph (b) Not strongly connected graph

Figure 1: Basic example of what is a small SCC

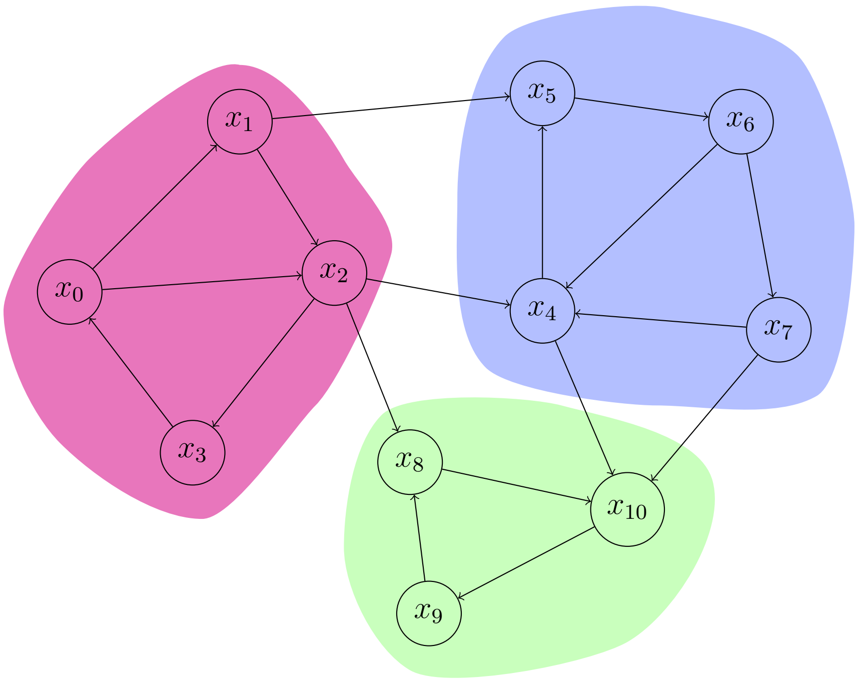


Figure 2: Example of a graph where each colored set of node is a – maximal – SCC

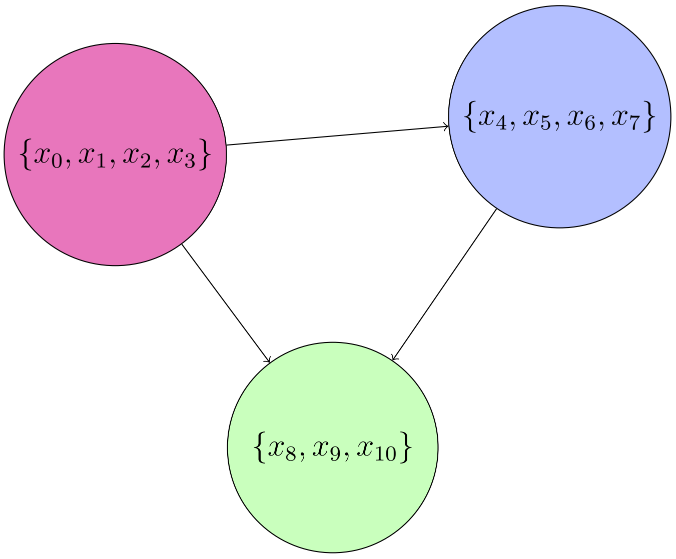


Figure 3: Reduced visualization of the graph represented in figure 2

3 A sequential set-based algorithm

3.1 Formalisation

Definition 4 (SCC mapping)**.** In the following algorithm, the SCCs are progressively tracked in a collection of disjoint sets through a map $\mathcal{S} : \mathcal{V} \longrightarrow \mathcal{P}(\mathcal{V})$, where $\mathcal{P}(\mathcal{V})$ is the powerset of $\mathcal{V}$, s.t. the following invariant is maintained:

$$\forall v, w \in \mathcal{V}, w \in \mathcal{S}(v) \iff \mathcal{S}(v) = \mathcal{S}(w) \tag{1}$$

Remark 2. In the following, the same notation $\mathcal{S}$ will be used to denote both the function defined above and the induced equivalence relation[1] since $\mathcal{S}$ associates to each node its class of equivalence.

Remark 3. In particular, $\forall v \in \mathcal{V}, v \in \mathcal{S}(v)$.

Definition 5 (SCC union)**.** Let UNITE be the function taking as parameters a map $\mathcal{S}$ as defined previously and two vertices u and v of $\mathcal{V}$ such that $\textsc{Unite}(\mathcal{S}, u, v)$ merges the two mapped sets $\mathcal{S}(u)$ and $\mathcal{S}(v)$ and maintains the invariant (1) by updating $\mathcal{S}$.

Let us give an example:
Let $\mathcal{V} = \{u, v, w\}$ such that there is the following mapping: $\mathcal{S}(u) = \{u\}$ and $\mathcal{S}(v) = \mathcal{S}(w) = \{v, w\}$.
Then, $\textsc{Unite}(\mathcal{S}, u, v) = \mathcal{S}(u) = \mathcal{S}(v) = \mathcal{S}(w) = \{u, v, w\}$.

Definition 6 (Successors set for a node)**.** Let $\mathcal{G} = (\mathcal{V}, \mathcal{E})$ and $v \in \mathcal{V}$. The set of successors of v in $\mathcal{G}$ is $\textsc{Post}(v)$ such that:

$$\forall w \in \textsc{Post}(v), (v, w) \in \mathcal{E}$$

[1]For the relation $(x, y) \mapsto x \Rightarrow^* y \ \wedge \ y \Rightarrow^* x$

3.2 The algorithm

See [3] for the original paper.

Algorithm 1: Sequential set-based SCC algorithm

```
Data: A graph $\mathcal{G} = (\mathcal{V}, \mathcal{E})$, a starting node $v_0$;
Result: A partition SCCs of $\mathcal{V}$ where each element of SCCs is a maximal
        set of strongly connected components of $\mathcal{G}$;
Initialize an empty set EXPLORED;
Initialize an empty set VISITED;
Initialize an empty stack R;
setBased($v_0$);
function setBased: $v \in \mathcal{V} \rightarrow$ None
    VISITED := VISITED $\cup \{v\}$;
    R.push($v$);
    foreach $w \in$ POST(v) do
        if $w \in$ EXPLORED then
            continue;
        end
        else if $w \notin$ VISITED then
            setBased($w$);
        end
        else
            while $\mathcal{S}(v) \neq \mathcal{S}(w)$ do
                $r$ := R.pop();
                UNITE($\mathcal{S}, r$, R.top());
            end
        end
    end
    if $v$ = R.top() then
        report SCC $\mathcal{S}(v)$;
        EXPLORED := EXPLORED $\cup \mathcal{S}(v)$;
        R.pop();
    end
```

sm: The algorithm should also explain how $\mathcal{S}$ is initialized.

3.3 Informal proof

Note that this proof is said informal only because it is not checked by a mechanized proof assistant. Both logical and mathematical arguments developed below are absolutely relevant.

Lemma 1. (First invariant)

$$\forall x, y \in \mathtt{R}, x \neq y \implies \mathcal{S}(x) \cap \mathcal{S}(y) = \varnothing$$

Note the misuse of the set notation $x, y \in \mathtt{R}$ which just means that x and y are in the stack $\mathtt{R}$.

Proof. Let $x, y \in \mathtt{R}$, $x \neq y$. We can assume w.l.o.g that $\mathtt{y} \preceq \mathtt{x}$ in $\mathtt{R}$. If $y \notin \mathcal{S}(x)$, then $\mathcal{S}(x)$ is disjoint from $\mathcal{S}(y)$.

Otherwise, let us assume that $y \in \mathcal{S}(x)$, *i.e.* $\mathcal{S}(x) = \mathcal{S}(y)$. Then, the *while*[2] loop will unstack all nodes of $\mathtt{R}$ until the successor of x in $\mathtt{R}$ is reached and add them with UNITE to $\mathcal{S}(x)$, so that the only representative of $\mathcal{S}(x)$ on $\mathtt{R}$ is x. ■

Remark 4. It is worth noting that the representative of a partial — with respect to the final result — SCC is the earliest node of this SCC to be visited regarding the graph traversal. This ensures that a representative on the stack is in fact the root of its SCC.

Lemma 2.

$$\biguplus_{r \in \mathtt{R}} \mathcal{S}(r) = \textsc{Live} := \textsc{Visited} \setminus \textsc{Explored}$$

Proof. The disjointness of all on-stack partial SCCs is given by lemma 1. Nodes from $\textsc{Visited} \setminus \textsc{Explored}$ are in $\mathtt{R}$ because they are being processed. So, $\textsc{Live} \subseteq \mathtt{R}$.
By L.6-7 of Algorithm 1, $\textsc{Visited} \subseteq \mathtt{R}$.
L.9-10 ensure that no explored node is pushed in $\mathtt{R}$.
L.24-25 keep the invariant by unstacking explored nodes from $\mathtt{R}$, so $\mathtt{R} \cap \textsc{Explored} = \varnothing$. Thus, $\mathtt{R} = \textsc{Visited} \setminus \textsc{Explored} = \textsc{Live}$. ■

Corollary 2.1 (Strong version)**.**

$$\forall v \in \textsc{Live}, \exists!\ r \in \mathtt{R} \cap \mathcal{S}(v), \mathcal{S}(v) = \mathcal{S}(r)$$

Proof. Let $v \in \textsc{Live} = \biguplus_{r \in \mathtt{R}} \mathcal{S}(r)$. v is in a unique partial SCC $\mathscr{S} := \mathcal{S}(v)$. Because of lemma 1, there cannot exist $x \neq y \in \mathtt{R}$ s.t. $\mathcal{S}(x) = \mathcal{S}(y) = \mathscr{S}$. Thus, there exists a unique $x \in \mathtt{R}$ s.t. $\mathcal{S}(x) = \mathscr{S}$ (and $x \in \mathtt{R} \cap \mathscr{S}$). ■

[2]See The algorithm

Corollary 2.2 (Weak version)**.**

$$\forall v \in \mathcal{V}, \forall w \in \textsc{Post}(v), w \in \textsc{Live} \implies \exists w' \in \mathtt{R}, \mathcal{S}(w') = \mathcal{S}(w)$$

Proof. Holds because of corollary 2.1. ■

Remark 5. In the algorithm 1, this property is maintained by L.16-18. These lines also illustrate how the algorithm "reads" the SCCs. Corollary 2.2 shows that when the mapped representatives of the top two nodes of $\mathtt{R}$ are united (until $\mathcal{S}(w') = \mathcal{S}(v) = \mathcal{S}(w)$ since w' has a path to v), then all united components are in the same SCC.

Remark 6. Because $\mathtt{R}$ only contains exactly one representative for each partial SCC (corollary 2.1 and remark 4), after each step of the main loop – *i.e.* the DFS – every partial SCC is actually maximal in the current set of visited nodes.

Theorem 1. The sequential algorithm 1 is correct, *i.e.* it returns a set of maximal SCCs.

Proof. Holds by remark 6. ■

3.4 Prerequisites for the formal proof

Since the informal proof seems to be convincing, the formal – checked automatically – proof can be written in Isabelle (HOL) based on the basis of the reasoning developed above.

3.4.1 Environment setup

The first definitions should be the different structures used in the algorithm. In particular, a record containing all the sets needed and described in the pseudo-code of algorithm 1. The environment has a generic type parameter, which is used to represent the type of the nodes in the graph (often integers):

```
record 'v env =
  𝓢 ::  "'v ⇒ 'v set"
  explored ::  "'v set"
  visited ::  "'v set"
  sccs ::  "'v set set"
  stack ::  "'v list"
```

The following lines define a graph structure and some useful natural relations:

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

The use of `successors` instead of an adjacency matrix, for instance, is a consequence of the fact that the algorithm is only concerned with the topological ordering of the nodes. For instance, nodes can represent integers, logical propositions or sets of states in a proving system for example.

3.4.2 Reachability

Now that graphs are defined, the reachability can be defined. Defining an edge is simply some rewriting of being a successor of one node.

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

Regarding the reachability binary relation, a choice has to be made since there are several ways to define it. In particular, there are two possible keywords, `inductive` and `fun`, respectively for an inductive or recursive definition. If both definitions are valid, the inductive one is kept for the following reasons. Although a recursive definition allows one to do some rewriting in the middle of terms, a recursive definition expresses both the positive and negative information[3] whereas the inductive one only expresses the positive information directly. Therefore, with an inductive definition, the negative information has to be proved. One would be right to argue that it would be more convenient to be able to tell without proving it that two nodes are not reachable from each other, but this does not interest us for the following. Another important point is that there is no datatype for a recursive definition, especially in this case with the transitive closure of the $\Rightarrow^*$ relation. Thus, the choice of the inductive definition is not a choice of simplicity but of necessity. Lastly, Isabelle will generate a simple inductive rule for the proofs split into the reflexive case, which stands in the definition, and the transitive case, which has to be proved.

```
inductive reachable where
  reachable_refl[iff]:  "reachable x x"
| reachable_succ[elim]:  "⟦edge x y; reachable y z⟧ ⟹ reachable x z"
```

In order to be able to use those relations in the proofs later, it is essential to prove a list of lemmas, namely all the different natural properties that Isabelle cannot deduce[4] from nothing[5]. For instance, the following lemmas are essential.

```
lemma succ_reachable:
    assumes "reachable x y" and "edge y z"
    shows"reachable x z"
    using assms by induct auto
```

Mathematical writing: $\forall x, \forall y, \forall z, (x \Rightarrow^* y \wedge y \Rightarrow z) \Longrightarrow x \Rightarrow^* z$

```
lemma reachable_trans:
    assumes y:  "reachable x y" and z:  "reachable y z"
    shows "reachable x z"
    using assms by induct auto
```

Mathematical writing: $\forall x, \forall y, \forall z, (x \Rightarrow^* y \wedge y \Rightarrow^* z) \Longrightarrow x \Rightarrow^* z$

As the formal proofs will enventually deal with strongly connected components, it is also essential to formally define SCCs. For the purpose of the proof, the property of being a SCC is called `sub_scc` and being a *maximal* SCC is called `is_scc` :

[3]In this case, the positive information designates the fact of being reachable and the negative information designates the fact of not being reachable.

[4]That is an abuse of language. The idea is for example that for the moment, there is no formal link between `edge` and `reachable`. The goal is to formalize it so Isabelle is logically able to both use and simplify some results in the proofs.

[5]There is actually a theorem fetcher that is particularly useful to find a basic set of lemmas.

```
definition is_subscc where
    "is_subscc S ≡ ∀ x ∈ S. ∀ y ∈ S. reachable x y"
```
Mathematical writing: A set S is a SCC if $\forall x \in S, \forall y \in S, x \Rightarrow^* y$

```
definition is_scc where
    "is_scc S ≡ S ≠ {} ∧ is_subscc S
    ∧ (∀ S'. S ⊆ S' ∧ is_subscc S' ⟶ S' = S)"
```
Mathematical writing: A non-empty SCC S is maximal if for all SCC S', $S \subseteq S' \Longrightarrow S' = S$

Once again, there are some lemmas to prove, such as telling Isabelle when an element can be added to a SCC, or that two vertices that are reachable from each other are in the same SCC, or that two SCCs having a common element are identical.

3.4.3 Equivalence relation and graph partition

In the algorithm 1, the SCCs are progressively tracked in `sccs` and the equivalence relation $\mathcal{S}$ is updated with the UNITE function. In Isabelle, a first recursive definition was written as follows:

```
function unite ::  "'v ⇒ 'v ⇒ 'v env ⇒ 'v env" where
"unite v w e =
  (if (𝒮 e v = 𝒮 e w) then e
  else let r = hd(stack e);
           r'= hd(tl(stack e));
           joined = 𝒮 e r ∪ 𝒮 e r;
           e'= e⦇
              stack := tl(stack e),
              𝒮 := (λ n.  if n ∈ joined then joined else 𝒮 e n)
           ⦈
  in unite v w e')"
  by pat_completeness auto
```

However, this definition makes the proofs too difficult due to the recursion. An imperative version was therefore written:

```
definition unite ::  "'v ⇒ 'v ⇒ 'v env ⇒ 'v env" where
  "unite v w e ≡
     let pfx = takeWhile (λx.  w ∉ 𝒮 e x) (stack e);
         sfx = dropWhile (λx.  w ∉ 𝒮 e x) (stack e);
         cc = ⋃ {𝒮 e x | x.  x ∈ set pfx ∪ {hd sfx}}
     in e⦇𝒮 := λx.  if x ∈ xx then cc else 𝒮 e x, stack := sfx⦈"
```

The idea of this definition is to create a partition of `stack e = pfx @ sfx` such that `pfx` contains the nodes which are to be merged into $\mathcal{S}$ `e w` and `sfx` contains the root of $\mathcal{S}$ `e w` followed by the rest of the stack. Then, `cc` – which stands for *connected component* – contains all the nodes which are equivalent to `w` in the sub-graph currently explored. The function `takeWhile` applied to a boolean function `P`[6] seen as a property and a list `xs` returns the elements of `xs` which satisfy `P` and stops to the first element not satisfying P. The function `dropWhile` is the opposite of `takeWhile`. Both the imperative and recursive versions of `unite` are equivalent.

3.4.4 Ordering relation

In the proof, a precedence relation[7] noted $\bullet \preceq \bullet$ in $\bullet$ will be needed on the stack. Let x and y be two nodes and R be a stack. Informally, x precedes y in R if y was pushed in R before x (see FIGURE 4).

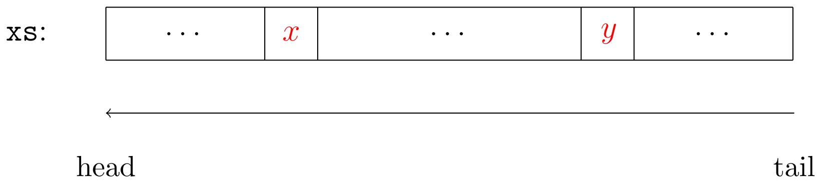


Figure 4: The ordering relation on stacks

Definition 7 (Ordering relation). Let x and y be two nodes and xs be a stack.

$$x \preceq y \text{ in } xs \equiv \exists\, h,\ \exists\, r,\ (xs = h@[x]@r) \wedge (y \in [x]@r)$$

The idea is to later use the following property: if $x \preceq y$ in xs, then $y \Rightarrow^* x$. It is defined in Isabelle as follows:

```
definition precedes ("_ ≼ _ in _" [100,100,100] 39) where
    "x ≼ y in xs ≡ ∃h r.  xs = h @ (x # r) ∧ y ∈ set (x # r)"
```

All the different properties (*i.e.* lemmas) which follow this definition in the Isabelle implementation are detailed in the natural mathematical writing in Appendix. The right part of the notation represents the orders of priority for each operand since $\preceq$ is an infix operator.

3.4.5 Implementation of the algorithm

Now that the environment is set up, the actual algorithm – seen as a function – can be implemented. Since Isabelle does not support loops, the implementation will be split

[6] `P :: 'a ⇒ bool`

[7] In fact, a total order is being defined on stacks.

into two mutually recursive functions. The main function is called `dfs` and takes its name after the Depth First Search algorithm because the algorithm 1 roughly consists in a deep traversal of a graph. The second function is called `dfss` and represents the *while* loop of the algorithm 1. The two functions are mutually recursive because they recursively call each other. In particular, `dfss` will call either itself or `dfs`, depending on the case.

```
function dfs ::  "'v ⇒ 'v env ⇒ 'v env" and
         dfss::  "'v ⇒ 'v set ⇒ 'v env ⇒ 'v env" where
"dfs v e =
    (let e1 = e⦇visited := visited e ∪ {v}, stack := (v # stack e)⦈;
         e' = dfss v (successors v) e1
    in if v = hd(stack e')
         then e'⦇sccs:=sccs e' ∪ 𝒮 e' v, explored:=explored e' ∪ (𝒮 e' v),
stack:=tl(stack e')⦈
         else e')"
| "dfss v vs e =
    (if vs = {} then e
    else (let w = SOME x.  x ∈ vs
         in (let e' = (if w ∈ explored e then e
                  else if w ∉ visited e then dfs w e
                  else unite v w e)
             in dfss v (v - {w}) e')))"
  by pat_completeness (force+)
```

The two last keywords require explanations as well : `pat_completeness` stands for *pattern completeness* and ensures that there is no missing patterns. The keyword `force` is used[8] to help Isabelle know – by proving it – that both `dfs` and `dfss` are actually functions and that those functions are well defined with respect to the usual logical and mathematical meaning.

[8]`force` is more aggressive in instantiation and seems to find the right instance.

3.5 Formal proof

3.5.1 General scheme

As the algorithm is composed of two mutually recursive functions, the correctness of the algorithm is proved by induction on the environment structure (cf 3.4.1). Since both `dfs` and `dfss` are quite complex, the proof is split into several parts. The idea is to prove for each function that its execution given some pre-conditions on the input environment implies some post-conditions on the output environment. Then, it has to be made for the mutually recursive calls as well, so that given the same pre-conditions on one function, the pre-conditions on the other function are also satisfied. Finally, it has to be proved that if the pre-conditions are satisfied for one function, and if the pre-conditions implie the post-conditions on the other function, then the post-conditions are also satisfied for the first function.

3.5.2 Well-formedness of the environment

The whole proof relies on one big invariant regarding the environment structure. It defines the fact for an environment to be well-formed. This invariant is a conjunction of several properties and is defined as follows:

```
definition wf_env where
  "wf_env e ≡
     distinct (stack e)
   ∧ set (stack e) ⊆ visited e
   ∧ explored e ⊆ visited e
   ∧ explored e ∩ set (stack e) = {}
   ∧ (∀ v w.  w ∈ 𝒮 e v ⟷ (𝒮 e v = 𝒮 e w))
   ∧ (∀v ∈ set (stack e).∀ w ∈ set (stack e).v ≠ w ⟶ 𝒮 e v ∩ 𝒮 e w = {})
   ∧ (∀ v.  v ∉ visited e ⟶ 𝒮 e v = {v})
   ∧ ⋃ {𝒮 e v | v.  v ∈ set (stack e)} = visited e - explored e
   ∧ (∀ x y.  x ≼ y in stack e ⟶ reachable y x)
   ∧ (∀ x.  is_subscc (𝒮 e x))
   ∧ (∀ x ∈ explored e.  ∀ y.  reachable x y ⟶ y ∈ explored e)
   ∧ (∀ S ∈ sccs e.  is_scc S)"
```

Let us take a closer look to this invariant, taken in the same order as the definition above:

- First, the stack is a set of distinct elements.
- All elements of the stack are visited.
- The set of explored nodes is a subset of the set of visited nodes.
- Explored nodes cannot be in the stack.

- The three next properties are about the equivalence relation $\mathcal{S}$.
- The union of the sets of equivalent nodes in the stack is equal to the set of visited nodes minus the set of explored nodes.
- A node in the stack can reach all nodes before it in the stack (*i.e.* pushed after)
- $\mathcal{S}$ represents a set of strongly connected components (not maximal).
- For all explored nodes, the sub-graph induced by their successors is totally explored
- `sccs` is a set of maximal SCCs

These properties are natural and most of them are easy to prove.

It is also useful to induce a notion of monotonicity on the environments during the execution of the algorithm. This is define as follows through the definition of an ordering relation on environments:

```
definition sub_env where
"sub_env e e' ≡
   visited e ⊆ visited e'
 ∧ explored e ⊆ explored e'
 ∧ (∀ v.  𝒮 e v ⊆ 𝒮 e' v)
 ∧ (⋃{𝒮 e v | v.  v ∈ set (stack e)}) ⊆ (⋃{𝒮 e' v | v.  v ∈ set (stack e')})"
```

3.5.3 `dfs` pre- and post-conditions

The pre-conditions of `dfs` are rather simple. The environment must be well-formed and the node must not be visited. There is also a condition on the reachability of the nodes in the stack and the node on which the function is called, but once again this condition is rather natural to consider since `dfs` is performing a DFS graph traversal:

```
definition pre_dfs where
 "pre_dfs v e ≡
   wf_env e
 ∧ v ∉ visited e
 ∧ (∀ n ∈ set (stack e).  reachable n v)"
```

The post-conditions are a little more complex since it has to consider the new environment with the new visited / explored nodes, the new state of the stack and the updates in $\mathcal{S}$:

```
definition post_dfs where
"post_dfs v prev_e e ≡
```

```
  wf_env e
∧ (∀ x.  reachable v x ⟶ x ∈ visited e)
∧ sub_env prev_e e
∧ (∀ n ∈ set (stack e).  reachable n v)
∧ (∃ ns.  stack prev_e = ns  (stack e))
∧ (∀ m n.  m  ≼  n in prec_e ⟶
     (∀ u ∈ 𝒮 prev_e m.  reachable u v ∧ reachable v n ⟶ 𝒮 e m = 𝒮 e n))
∧ ((v ∈ explored e ∧ stack e = stack prev_e) ∨ v ∈ 𝒮 e (hd (stack e)))"
```

4 Appendix

4.1 Some lemmas

Those lemmas refer to the precedence relation introduced in SECTION 3.4.4.

Let x, y, z be three nodes, and let xs, ys, zs be three lists of nodes representing stacks. By abuse of language, if an element is on a stack, it is in the set of elements contained in the stack so the following statement can be written: x is on $xs \iff x \in xs$. However, xs in not seen as the set representing xs since an element may occur several times in a stack. The operator @ denotes the concatenation and operates on two lists: $[x_0, \ldots, x_n]@[y_0, \ldots, y_m] = [x_0, \ldots, x_n, y_0, \ldots, y_m]$.

(i) $x \preceq y \text{ in } xs \implies (x \in xs) \wedge (y \in xs)$

(ii) $y \in [x]@xs \implies x \preceq y \text{ in } ([x]@xs)$

(iii) $x \neq z \implies (x \preceq y \text{ in } ([z]@zs) \implies x \preceq y \text{ in } zs)$

(iv) $(y \preceq x \text{ in } ([x]@xs)) \wedge (x \notin xs) \implies (x = y)$

(v) $y \in (ys@[x]) \implies y \preceq x \text{ in } (ys@[x]@xs)$

(vi) $(x \preceq x \text{ in } xs) = (x \in xs)$

(vii) $x \preceq y \text{ in } xs \implies x \preceq y \text{ in } (ys@xs)$

(viii) $x \notin ys \implies (x \preceq y \text{ in } (ys@xs) \iff x \preceq y \text{ in } xs)$

(ix) $x \preceq y \text{ in } xs \implies x \preceq y \text{ in } (xs@ys)$

(x) $y \notin ys \implies x \preceq y \text{ in } (xs@ys) \iff x \preceq y \text{ in } xs$

(xi)(transitivity)
$(x \preceq y \text{ in } xs) \wedge (y \preceq z \text{ in } xs) \wedge \underbrace{(\forall\ 0 \leq i < j \leq \text{length}(xs), xs[i] \neq xs[j])}_{\text{all elements of } xs \text{ are distinct}} \implies x \preceq z \text{ in } xs$

(xi)(antisymmetry)
$(x \preceq y \text{ in } xs) \wedge (y \preceq x \text{ in } xs) \wedge \underbrace{(\forall\ 0 \leq i < j \leq \text{length}(xs), xs[i] \neq xs[j])}_{\text{all elements of } xs \text{ are distinct}} \implies x = y$

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