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Strongly Connected Components in graphs, formal proof of Tarjan1972 algorithm

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Plan

- motivation
- algorithm
- pre-/post-conditions
- imperative programs
- conclusion

.. joint work (in progress) with Ran Chen

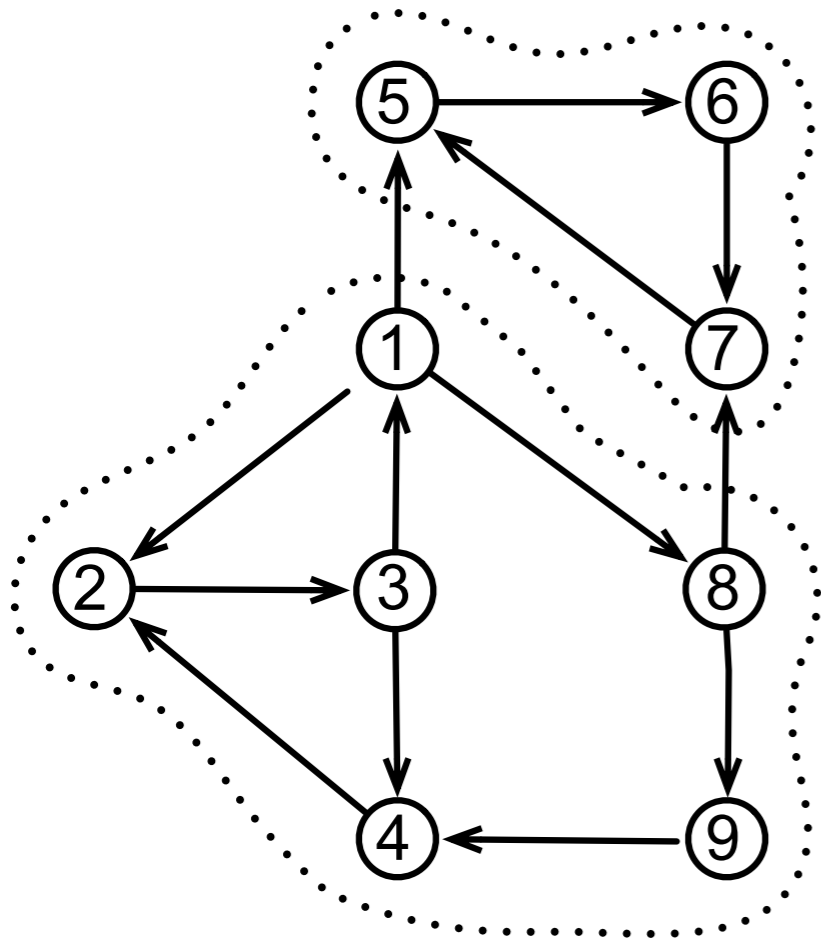
Motivation

- nice algorithms should have simple formal proofs
- to be fully published in articles or journals
- how to publish formal proofs ?
- Coq proofs seem to me unreadable (and by normal human ?)
- Why3 allows mix of automatic and interactive proofs
- first-order logic is easy to understand
- algorithms on graphs = a good testbed



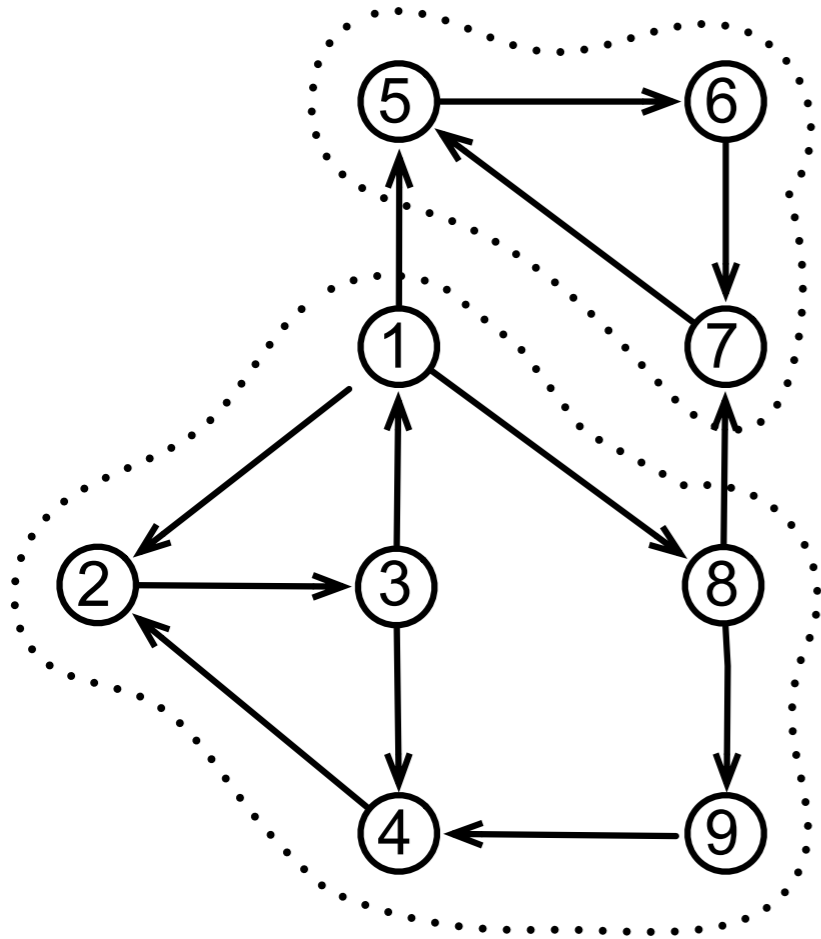
A one-pass linear-time algorithm

The algorithm (1/2)



- depth-first search algorithm
- with pushing non visited vertices into a working stack
- and computing oldest vertex reachable by at most a single « back-edge »
- when that oldest vertex is equal to currently visited vertex, a new strongly connected component is in the working stack on top of current vertex.
- then pop working stack until currently visited vertex

The algorithm (2/2)

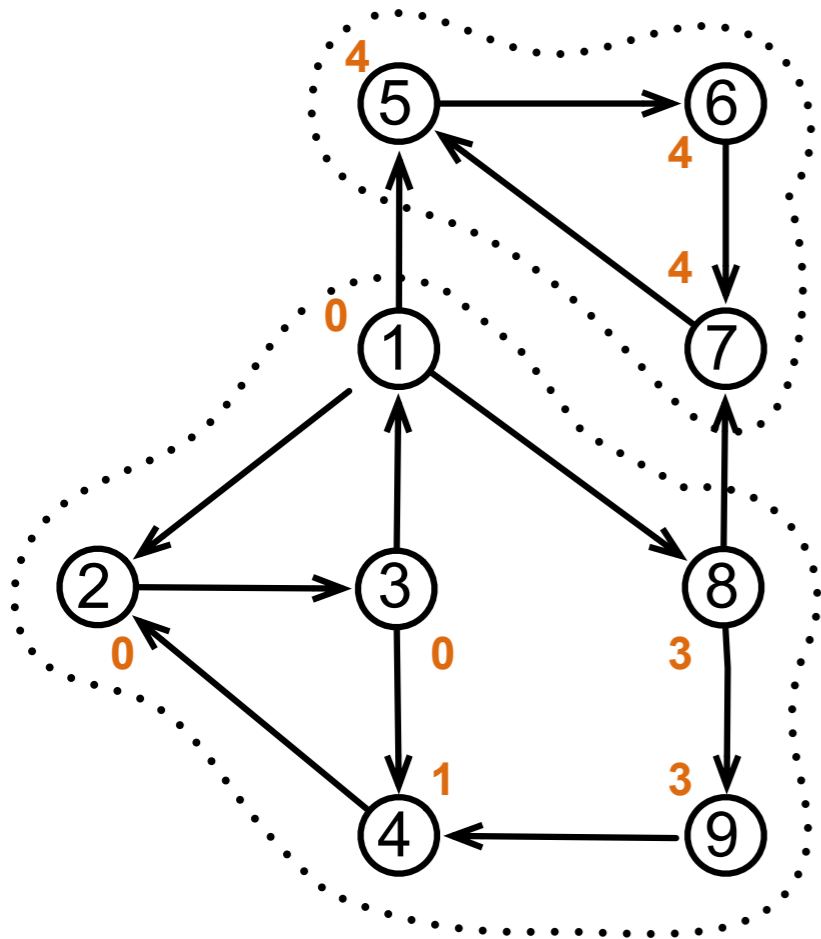


les valeurs successives de la pile

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 |
| | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 1 |
| | | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 2 |
| | | | 4 | 4 | 4 | 4 | 4 | 4 | 3 |
| | | | | 5 | 5 | 5 | 8 | 8 | 4 |
| | | | | | 6 | 6 | | 9 | 5 |
| | | | | | | 7 | | | 6 |

sens croissant du rang

The algorithm (2/2)



les valeurs successives de la pile

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 |
| | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 1 |
| | | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 2 |
| | | | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 3 |
| | | | | 5 | 5 | 5 | 5 | 5 | 5 | 4 |
| | | | | | 6 | 6 | 6 | 6 | 6 | 5 |
| | | | | | | 7 | 7 | 7 | 7 | 6 |
| | | | | | | | 8 | 8 | 8 | |
| | | | | | | | | 9 | 9 | |

sens croissant du rang

Proof in algorithms book

- consider the spanning trees (forrest)
- Christmas tree structure of strongly connected components
- 2-3 lemmas about ancestors in spanning trees

LEMMA 10. Let v and w be vertices in G which lie in the same strongly connected component. Let F be a spanning forest of G generated by repeated depth-first search. Then v and w have a common ancestor in F . Further, if u is the highest numbered common ancestor of v and w , then u lies in the same strongly connected component as v and w .

- give the program
- that proof  program

The program (1/3)

- a functional version with lists and finite sets
- the working stack is a list

```
function rank (x: vertex) (s: list vertex): int =  
  match s with  
  | Nil → max_int()  
  | Cons y s' → if x = y && not (lmem x s') then length s' else rank x s'  
end
```

```
function max_int (): int = cardinal vertices
```

```
let rec split (x :  $\alpha$ ) (s: list  $\alpha$ ) : (list  $\alpha$ , list  $\alpha$ ) =  
returns{(s1, s2) → s1 ++ s2 = s}  
returns{(s1, _) → lmem x s → is_last_of x s1}  
  match s with  
  | Nil → (Nil, Nil)  
  | Cons y s' → if x = y then (Cons x Nil, s') else  
    let (s1', s2) = split x s' in  
    ((Cons y s1'), s2)  
end
```

The program (2/3)

- *blacks*, *grays* are sets of vertices; *sccs* is a set of sets of vertices
- naming conventions:
 - x*, *y*, *z* for vertices; *b* for black sets; *s* for stacks;
 - cc* for connected components;
 - sccs* for sets of connected components

```
let rec dfs1 x blacks (ghost grays) stack sccs =  
  let m = rank x (Cons x stack) in  
  let (m1, b1, s1, sccs1) =  
    dfs' (successors x) blacks (add x grays) (Cons x stack) sccs in  
  if m1 ≥ m then  
    let (s2, s3) = split x s1 in  
    (max_int(), add x b1, s3, add (elements s2) sccs1)  
  else  
    (m1, add x b1, s1, sccs1)
```

The program (3/3)

```
with dfs' roots blacks (ghost grays) stack sccs =
  if is_empty roots then
    (max_int(), blacks, stack, sccs)
  else
    let x = choose roots in
    let roots' = remove x roots in
    let (m1, b1, s1, sccs1) =
      if lmem x stack then
        (rank x stack, blacks, stack, sccs)
      else if mem x blacks then
        (max_int(), blacks, stack, sccs)
      else
        dfs1 x blacks grays stack sccs in
    let (m2, b2, s2, sccs2) =
      dfs' roots' b1 grays s1 sccs1 in
    (min m1 m2, b2, s2, sccs2)
```



Pre-/Post-conditions

Pre/Post-conditions (1/3)

```
let rec dfs1 x blacks (ghost grays) stack sccs =  
requires {mem x vertices} (* R1 *)  
requires {access_to grays x} (* R2 *)  
requires {not mem x (union blacks grays)} (* R3 *)
```

(monotony *)*

```
returns {(_, b, s, _) → ∃s'. s = s' ++ stack ∧ subset (elements s') b} (* M1 *)  
returns {(_, b, _, _) → subset blacks b} (* M2 *)  
returns {(_, _, _, sccs_n) → subset sccs sccs_n} (* M3 *)
```

Pre/Post-conditions (2/3)

stack



x



s



m

y

x



$\text{sccs} \subseteq \text{sccs}_n$

$\text{blacks} \subseteq b$

$m \leq \text{rank } y \text{ stack}$

$m \leq \text{rank } x \text{ stack}$

Pre/Post-conditions (3/3)

```
with dfs' roots blacks (ghost grays) stack sccs =  
requires {subset roots vertices} (* R1 *)  
requires { $\forall x. \text{mem } x \text{ roots} \rightarrow \text{access\_to } \text{grays } x$ } (* R2 *)
```

```
(* post conditions *)
```

```
returns {(_, b, _, _)  $\rightarrow$  subset roots (union b grays)} (* E1 *)
```

```
returns {(m, _, s, _)  $\rightarrow \forall x. \text{mem } x \text{ roots} \rightarrow m \leq \text{rank } x \text{ s}$ } (* E2 *)
```

```
returns {(m, _, s, _)  $\rightarrow m = \text{max\_int}() \vee \exists x. \text{mem } x \text{ roots} \wedge \text{rank\_of\_reachable } m \text{ } x \text{ s}$ }
```

```
returns {(m, _, s, _)  $\rightarrow \forall y. \text{crossedgeto } s \text{ } y \text{ stack} \rightarrow m \leq \text{rank } y \text{ stack}$ } (* E4 *)
```

```
(* monotony *)
```

```
returns {(_, b, s, _)  $\rightarrow \exists s'. s = s' ++ \text{stack} \wedge \text{subset } (\text{elements } s') \text{ } b$ } (* M1 *)
```

```
returns {(_, b, _, _)  $\rightarrow \text{subset } \text{blacks } b$ } (* M2 *)
```

```
returns {(_, _, _, sccs_n)  $\rightarrow \text{subset } \text{sccs } \text{sccs\_n}$ } (* M3 *)
```


Graphs

```
type vertex
constant vertices: set vertex
function successors vertex : set vertex
axiom successors_vertices:
   $\forall x. \text{mem } x \text{ vertices} \rightarrow \text{subset } (\text{successors } x) \text{ vertices}$ 
predicate edge (x y: vertex) =
  mem x vertices  $\wedge$  mem y (successors x)
```

Paths

```
inductive path vertex (list vertex) vertex =  
  | Path_empty:  
     $\forall x: \text{vertex}. \text{path } x \text{ Nil } x$   
  | Path_cons:  
     $\forall x \ y \ z: \text{vertex}, l: \text{list vertex}.$   
     $\text{edge } x \ y \rightarrow \text{path } y \ l \ z \rightarrow \text{path } x \ (\text{Cons } x \ l) \ z$ 
```

```
predicate reachable (x z: vertex) =  
   $\exists l. \text{path } x \ l \ z$ 
```

```
predicate in_same_scc (x z: vertex) =  
   $\text{reachable } x \ z \wedge \text{reachable } z \ x$ 
```

```
predicate is_subsc (s: set vertex) =  
   $\forall x \ z. \text{mem } x \ s \rightarrow \text{mem } z \ s \rightarrow \text{in\_same\_scc } x \ z$ 
```

```
predicate is_scc (s: set vertex) =  
   $\text{is\_subsc } s \wedge (\forall s'. \text{subset } s \ s' \rightarrow \text{is\_subsc } s' \rightarrow s == s')$ 
```

Invariants (1/4)

```
predicate no_black_to_white (blacks grays: set vertex) =  
  ∀ x x'. edge x x' → mem x blacks → mem x' (union blacks grays)
```

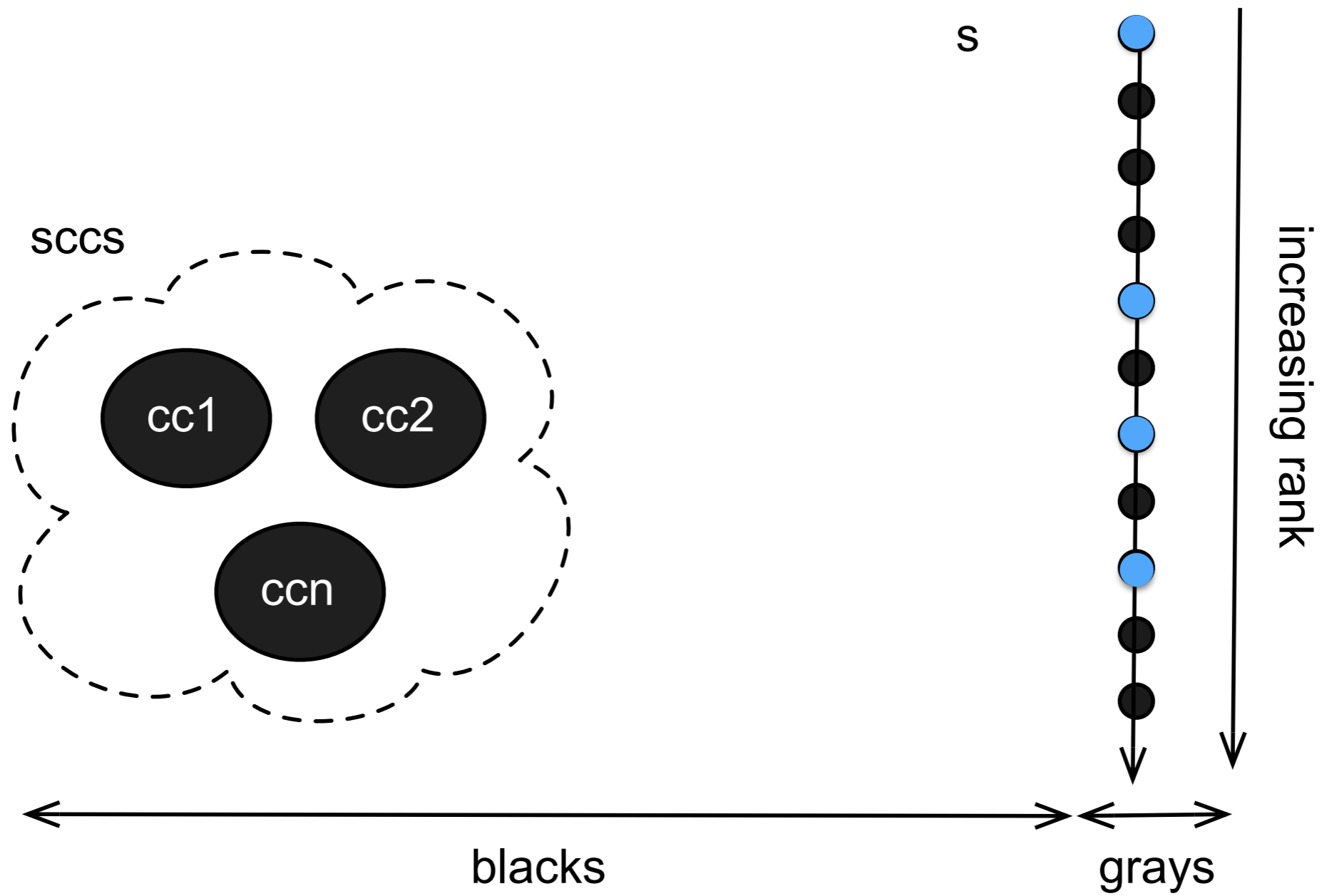
```
predicate wff_color (blacks grays: set vertex) (s: list vertex)  
  (sccs: set (set vertex)) =  
  inter blacks grays = empty ∧  
  (elements s) == union grays (diff blacks (set_of sccs)) ∧  
  (subset (set_of sccs) blacks) ∧  
  no_black_to_white blacks grays
```

$$\text{blacks} \cap \text{grays} = \emptyset$$

$$\text{elements } s = \text{grays} \cup \text{blacks} - (\text{set_of } \text{sccs})$$

$$(\text{set_of } \text{sccs}) \subseteq \text{blacks}$$

Invariants (2/4)



Invariants (3/4)

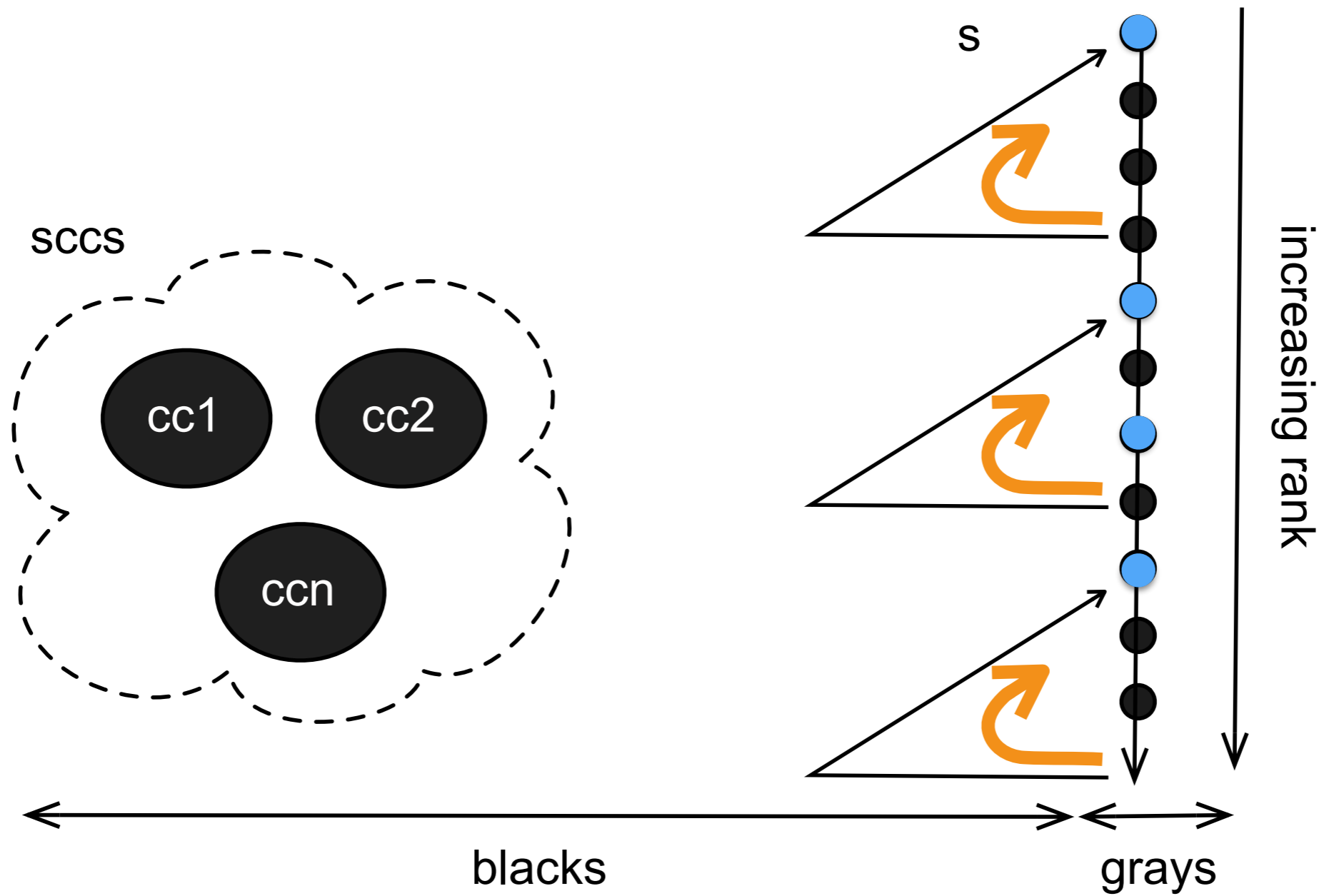
```
predicate wff_stack (blacks grays: set vertex) (s: list vertex)
  (sccs: set (set vertex)) =
```

```
wff_color blacks grays s sccs  $\wedge$ 
simplelist s  $\wedge$ 
subset (elements s) vertices  $\wedge$ 
```

```
( $\forall$ x y. mem x grays  $\rightarrow$  lmem y s  $\rightarrow$ 
  rank x s  $\leq$  rank y s  $\rightarrow$  reachable x y)  $\wedge$ 
```

```
( $\forall$ y. lmem y s  $\rightarrow$   $\exists$ x. mem x grays  $\wedge$ 
  rank x s  $\leq$  rank y s  $\wedge$  reachable y x)
```

Invariants (4/4)



Assertions

```
let m = rank x (Cons x stack) in
let (m1, b1, s1, sccs1) =
dfs' (successors x) blacks (add x grays) (Cons x stack) sccs in

if m1 ≥ m then begin
  let (s2, s3) = split x s1 in
  assert {s3 = stack};
  assert {subset (elements s2) (add x b1)};
  assert {is_subsc (elements s2) ∧ mem x (elements s2)};
  assert {∀y. in_same_scc y x → mem y (elements s2)};
  assert {is_scc (elements s2)};

  (max_int(), add x b1, s3, add (elements s2) sccs1) end
else begin

  (m1, add x b1, s1, sccs1) end
```

Assertions

```
assert { $\forall y. \text{in\_same\_scc } y \ x \rightarrow \text{mem } y \ (\text{elements } s2)$ };
```

- Coq proof: there exists x', y' with $x' \in s2 \wedge y' \notin s2 \wedge \text{edge } x' \ y'$

$y' \in s3 = \text{stack}$

$x' = x$ impossible because $m1 \leq \text{rank } y' \ s1 < \text{rank } x \ s1$

$x' \neq x$ impossible because crossed edge

$y' \in \text{SCCs}$ impossible because sccs disjoint from stack

y' is white

$x' = x$ impossible because successors are black

$x' \neq x$ impossible because no black to white

Pre/Post-conditions (1/3)

```
let rec dfs1 x blacks (ghost grays) stack sccs =
requires{mem x vertices} (* R1 *)
requires{access_to grays x} (* R2 *)
requires{not mem x (union blacks grays)} (* R3 *)
(* invariants *)
requires{wff_stack blacks grays stack sccs} (* I1a *)
requires{ $\forall cc. \text{mem } cc \text{ sccs} \leftrightarrow \text{subset } cc \text{ blacks} \wedge \text{is\_scc } cc$ } (* I2a *)
returns{(_, b, s, sccs_n)  $\rightarrow$  wff_stack b grays s sccs_n} (* I1b *)
returns{(_, b, _, sccs_n)  $\rightarrow \forall cc. \text{mem } cc \text{ sccs\_n} \leftrightarrow \text{subset } cc \text{ b} \wedge \text{is\_scc } cc$ } (* I2b *)
(* post conditions *)
returns{(_, b, _, _)  $\rightarrow$  mem x b} (* E1 *)
returns{(m, _, s, _)  $\rightarrow m \leq \text{rank } x \text{ s}$ } (* E2 *)
returns{(m, _, s, _)  $\rightarrow m = \text{max\_int}() \vee \text{rank\_of\_reachable } m \text{ x s}$ } (* E3 *)
returns{(m, _, s, _)  $\rightarrow \forall y. \text{crossedgeto } s \text{ y stack} \rightarrow m \leq \text{rank } y \text{ stack}$ } (* E4 *)
(* monotony *)
returns{(_, b, s, _)  $\rightarrow \exists s'. s = s' ++ \text{stack} \wedge \text{subset } (\text{elements } s') \text{ b}$ } (* M1 *)
returns{(_, b, _, _)  $\rightarrow \text{subset } \text{blacks } b$ } (* M2 *)
returns{(_, _, _, sccs_n)  $\rightarrow \text{subset } \text{sccs } \text{sccs\_n}$ } (* M3 *)
```



Towards imperative program

Assertions

```
let rec dfs1 x blacks (ghost grays) stack sccs (sn num) =
  requires {sn = cardinal (union grays blacks)  $\wedge$  subset (union grays blacks) vertices}
  (* invariants *)
  requires {wff_num sn num stack} (* I3a *)
  returns {(_, _, _, s, _, sn_n, num_n)  $\rightarrow$  wff_num sn_n num_n s} (* I3b *)
  (* post conditions *)
  returns {(sn_n, m, _, s, _, _, num_n)  $\rightarrow$  sn_n = m = max_int()  $\vee$ 
     $\exists$ y. lmem y s  $\wedge$  sn_n = num_n[y]  $\wedge$  m = rank y s} (* E5 *)

  let m = rank x (Cons x stack) in
  let (n1, m1, b1, s1, sccs1, sn1, num1) =
    dfs' (successors x) blacks (add x grays) (Cons x stack) sccs (sn + 1) num[x  $\leftarrow$  sn] in
  if n1  $\geq$  sn then begin
    let (s2, s3) = split x s1 in
    (max_int(), max_int(), add x b1, s3, add (elements s2) sccs1, sn1, num1) end
  else
    (n1, m1, add x b1, s1, sccs1, sn1, num1)
```

Assertions

```
predicate wff_num (sn: int) (num: map vertex int) (s: list vertex) =  
  ( $\forall x. \text{num}[x] < \text{sn} \leq \text{max\_int}()$ )  $\wedge$   
  ( $\forall x y. \text{lmem } x \text{ s} \rightarrow \text{lmem } y \text{ s} \rightarrow \text{num}[x] \leq \text{num}[y] \leftrightarrow \text{rank } x \text{ s} \leq \text{rank } y \text{ s}$ )
```


Assertions

```
let rec dfs1 x blacks (ghost grays) stack sccs sn num =
  let m = rank x (Cons x stack) in
  let n = !sn in
  incr sn; num := !num[x ← n];
  let (n1, m1, b1, s1, sccs1) =
    dfs' (successors x) blacks (add x grays) (Cons x stack) sccs sn num in
  assert {n1 ≥ n ↔ m1 ≥ m}; (** *)
  if n1 ≥ n then begin
    let (s2, s3) = split x s1 num in
    assert {s3 = stack};
    assert {subset (elements s2) (add x b1)};
    assert {is_subsc (elements s2) ∧ mem x (elements s2)};
    assert {∀y. in_same_scc y x → mem y (elements s2)};
    assert {is_scc (elements s2)};
    (max_int(), max_int(), add x b1, s3, add (elements s2) sccs1) end
  else begin
    assert {∃y. mem y grays ∧ rank y s1 < rank x s1 ∧ reachable x y};
    (n1, m1, add x b1, s1, sccs1) end
```


The background features four large, overlapping circles in vibrant colors: yellow, green, blue, and red. Each circle is outlined with a thick, dark blue border. The circles overlap in the center, creating a complex geometric pattern. The word "Conclusion" is centered over this pattern in a white, sans-serif font.

Conclusion

Conclusion

- readable proofs ?
- simple algorithms should have simple proofs
 to be shown with a good formal precision
- compare with other proof systems
- further algorithms (in next talks ?)
 - graphs represented with arrays + lists
 - topological sort, articulation points, scck, sscT
- Why3 is a beautiful system but not so easy to use !