Verifying C and Java programs

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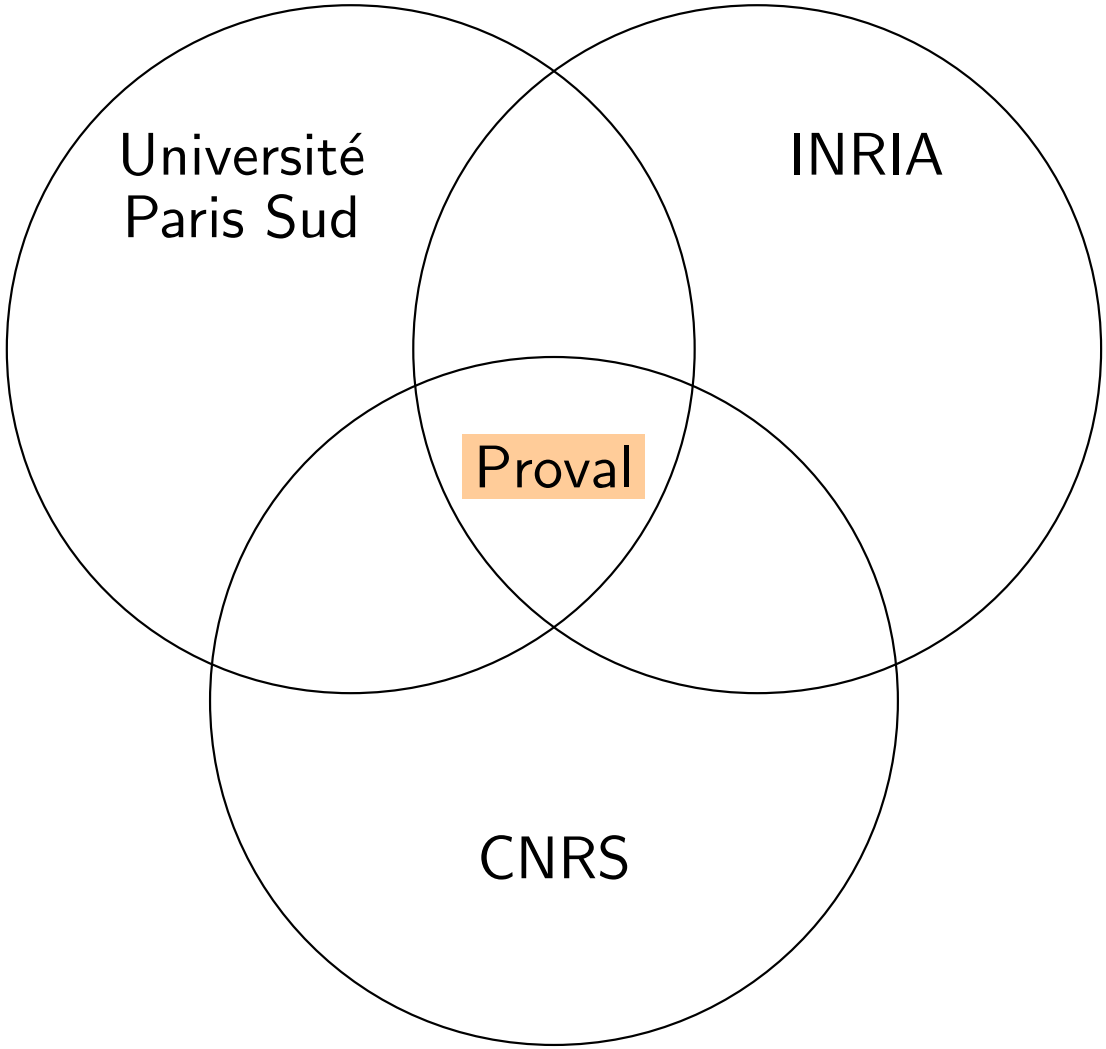
CNRS – Université Paris Sud

Queen Mary University – April 28th, 2005

The Proval project (proval.lri.fr)



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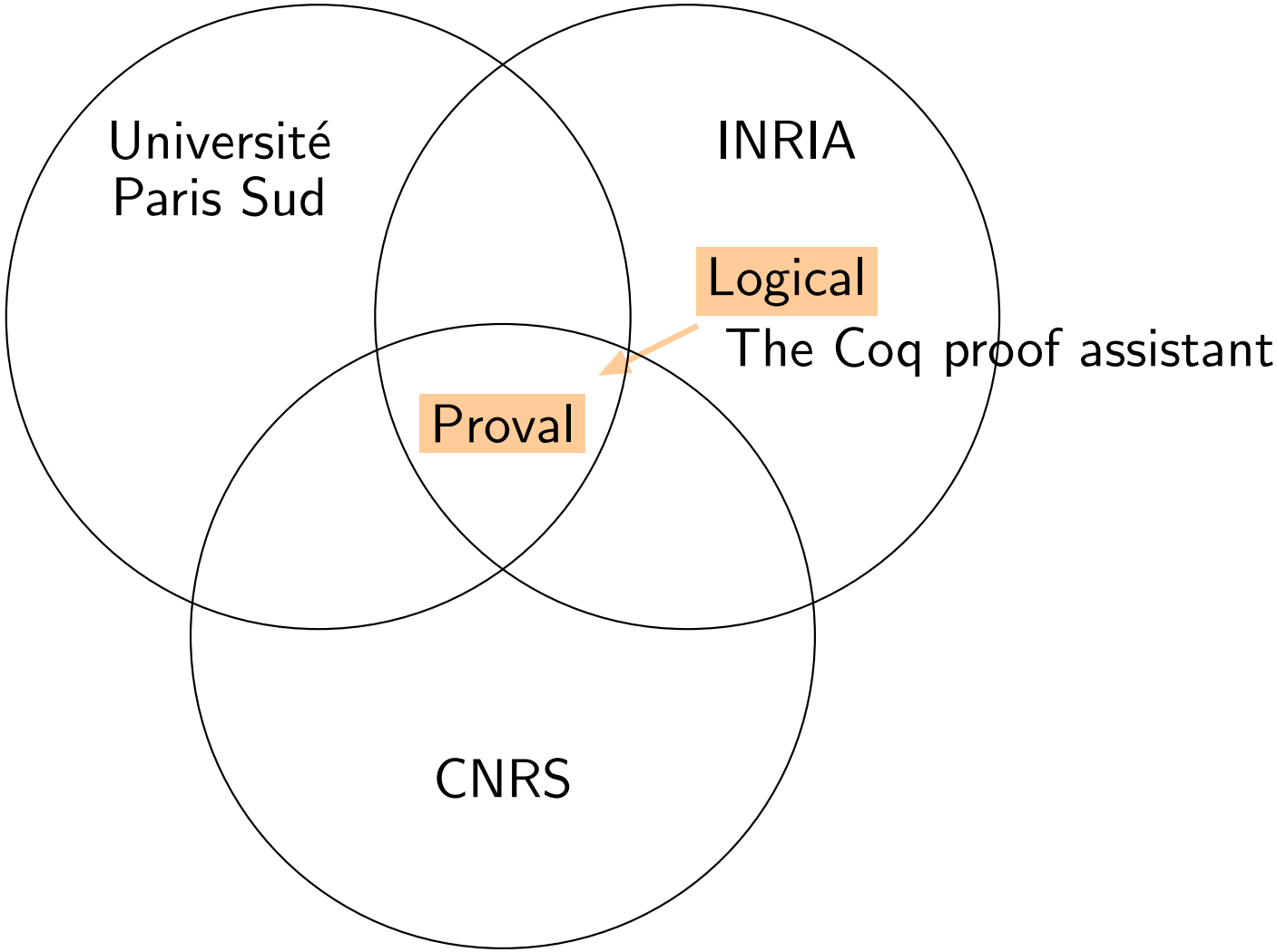

Credo

We are interested in verifying big properties of (small) programs
($\neq$ small properties of big programs e.g. BLAST at Microsoft)

We believe that

- program verification requires interactive proof
  (i.e. fully automatic proof is hopeless)
- verification tools must be safe

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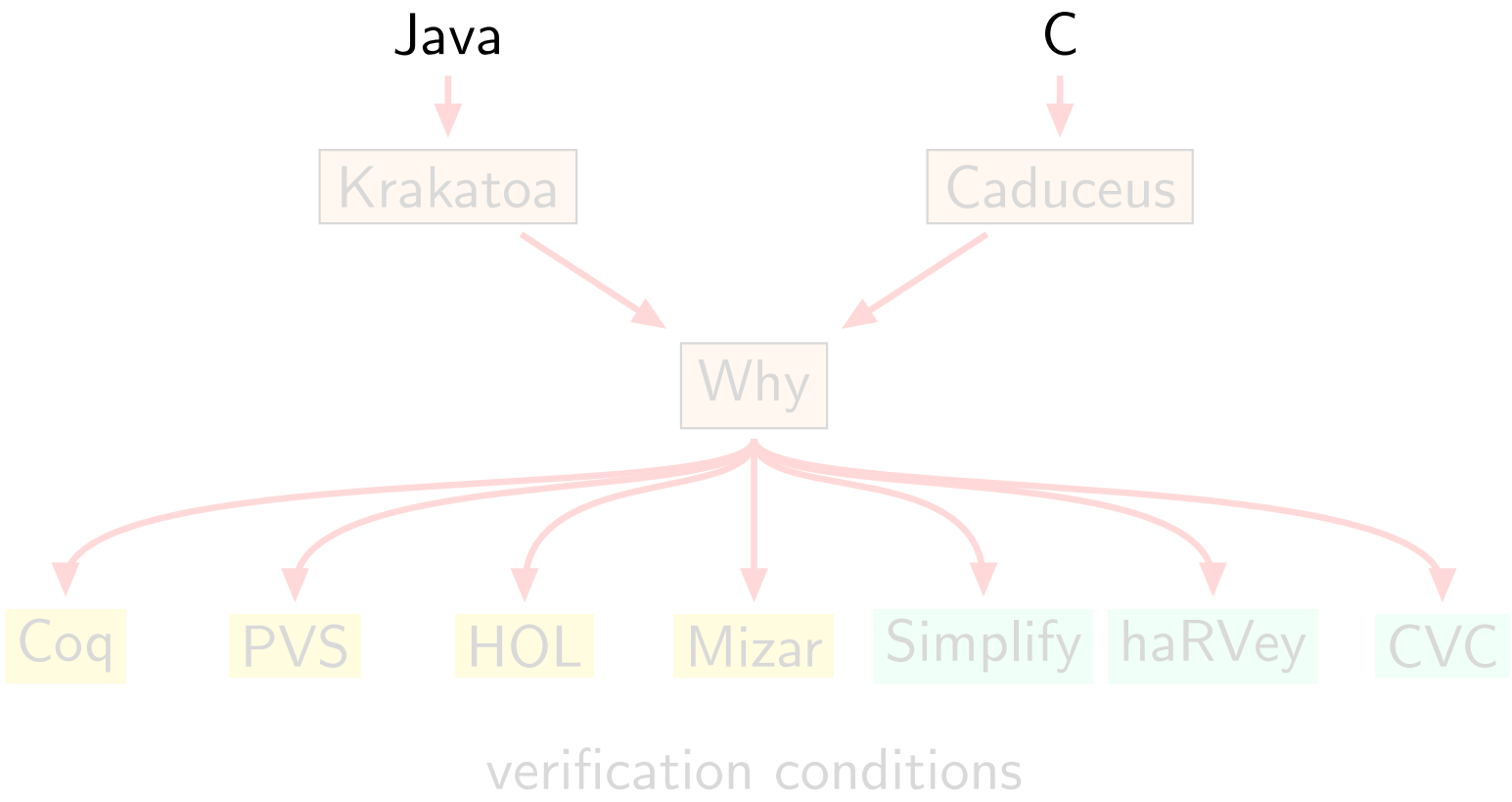

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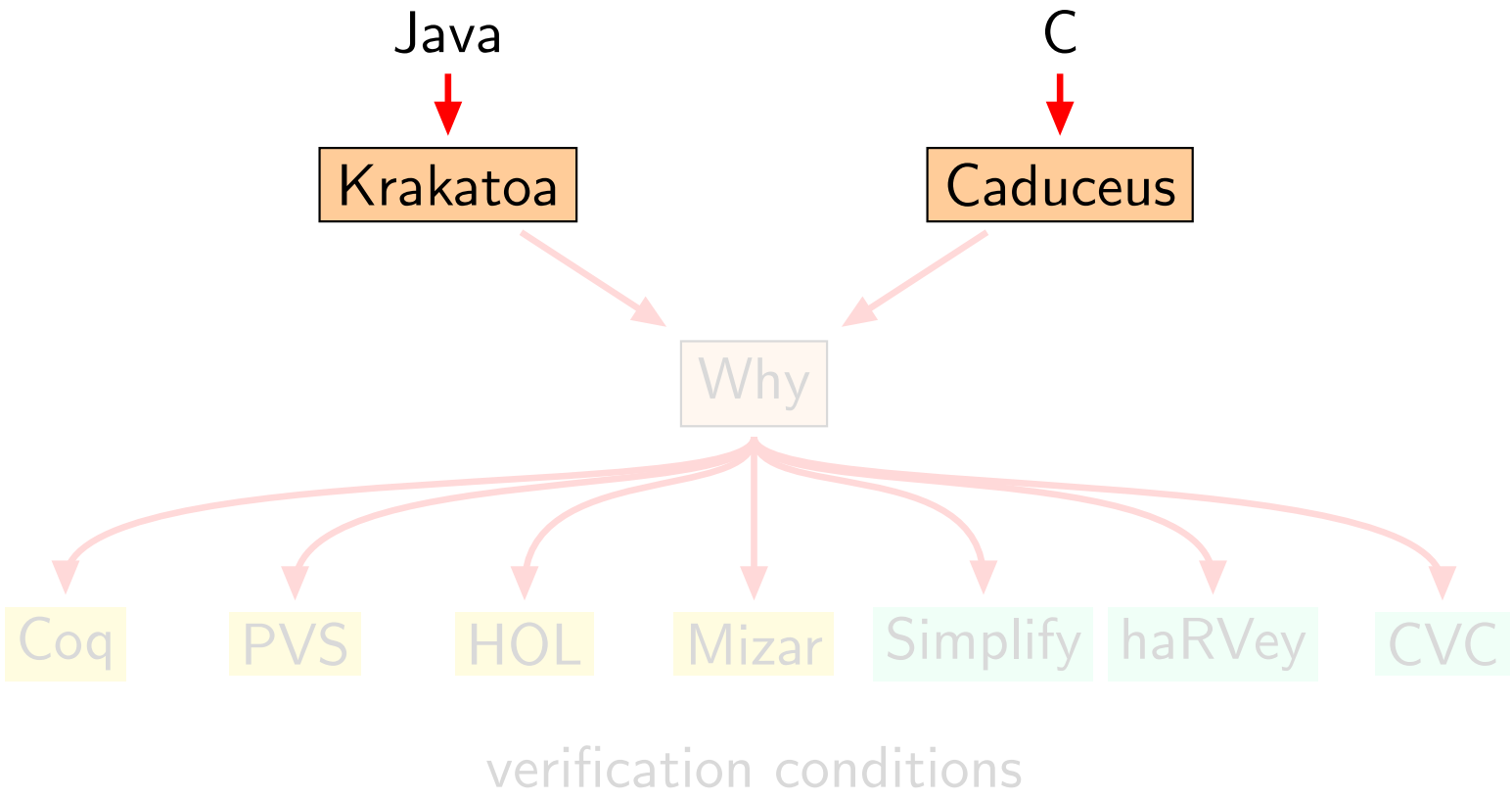

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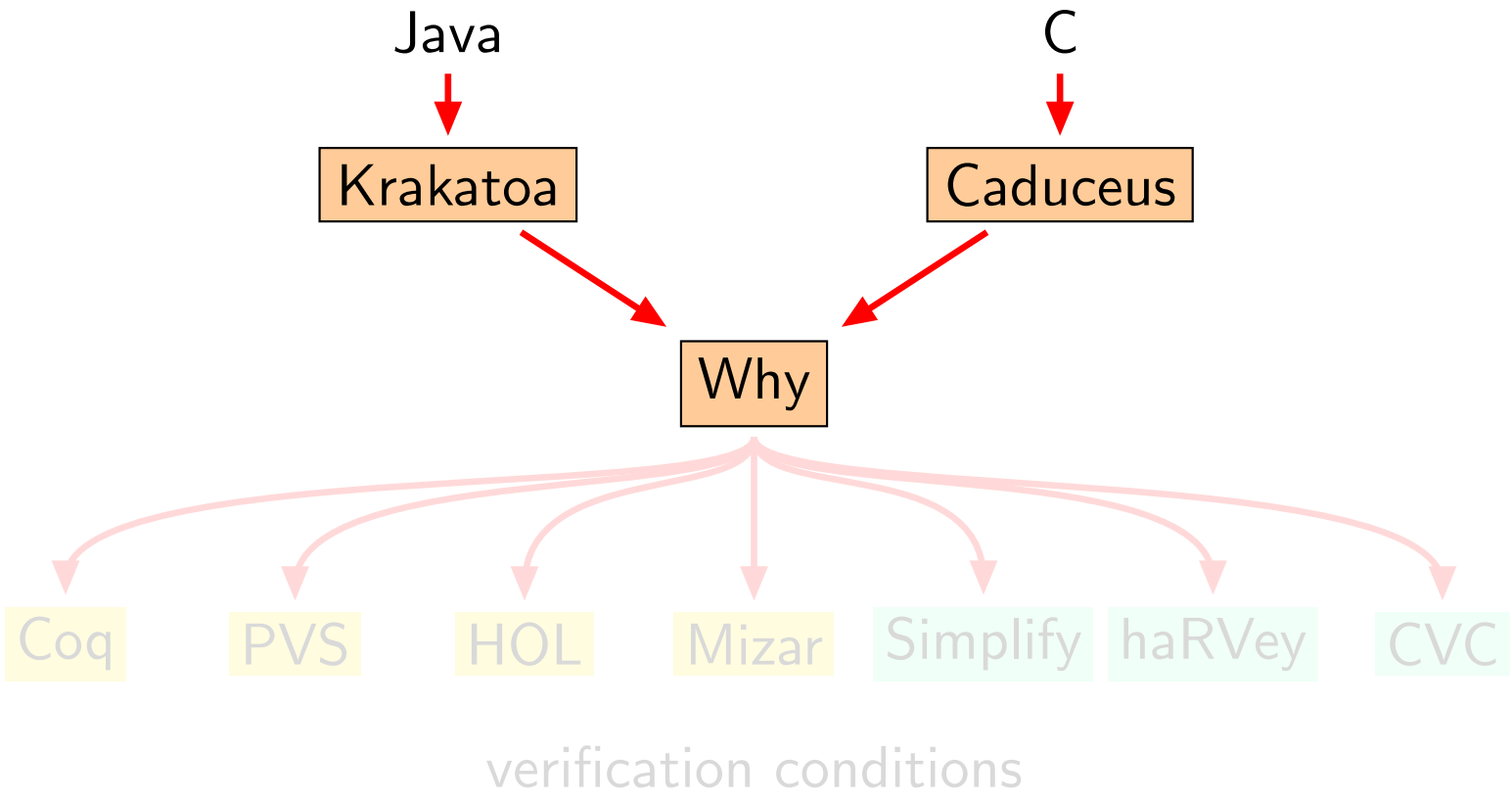

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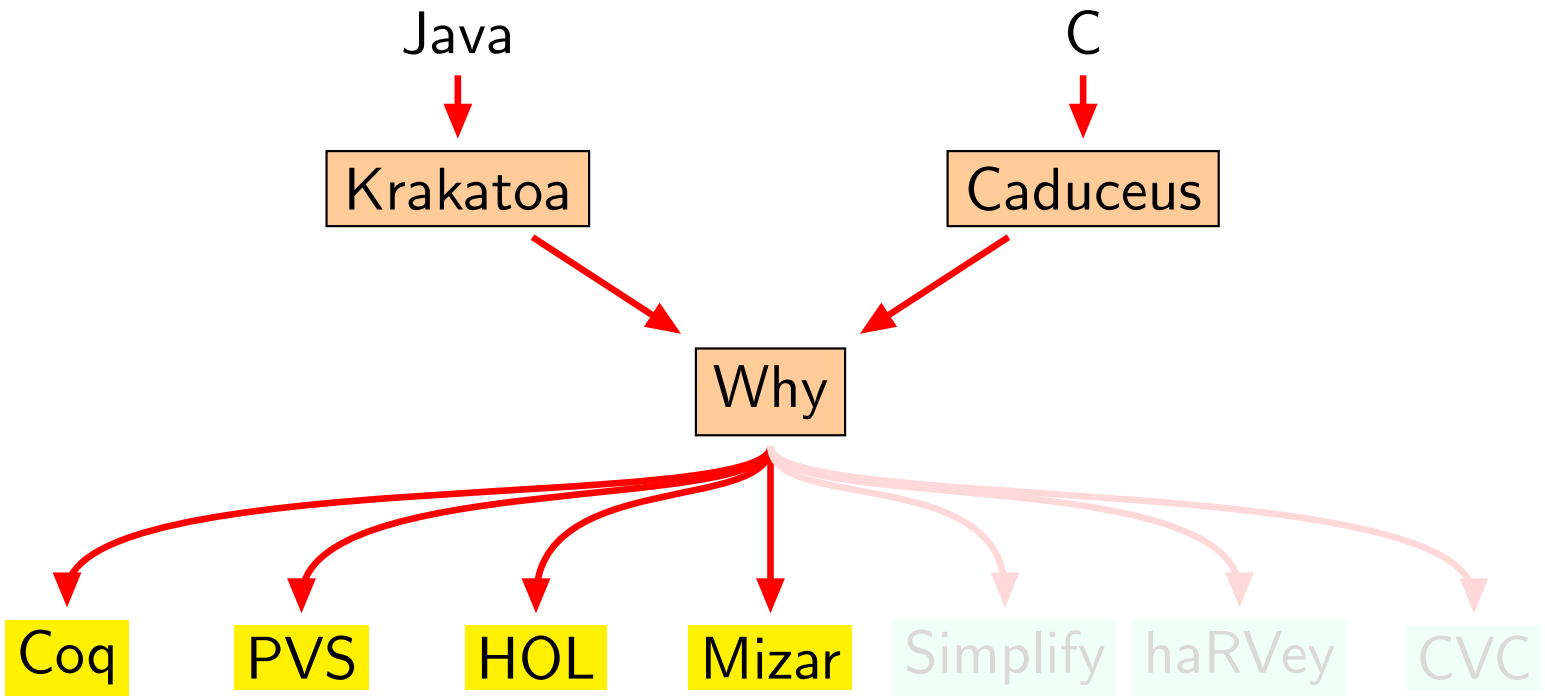

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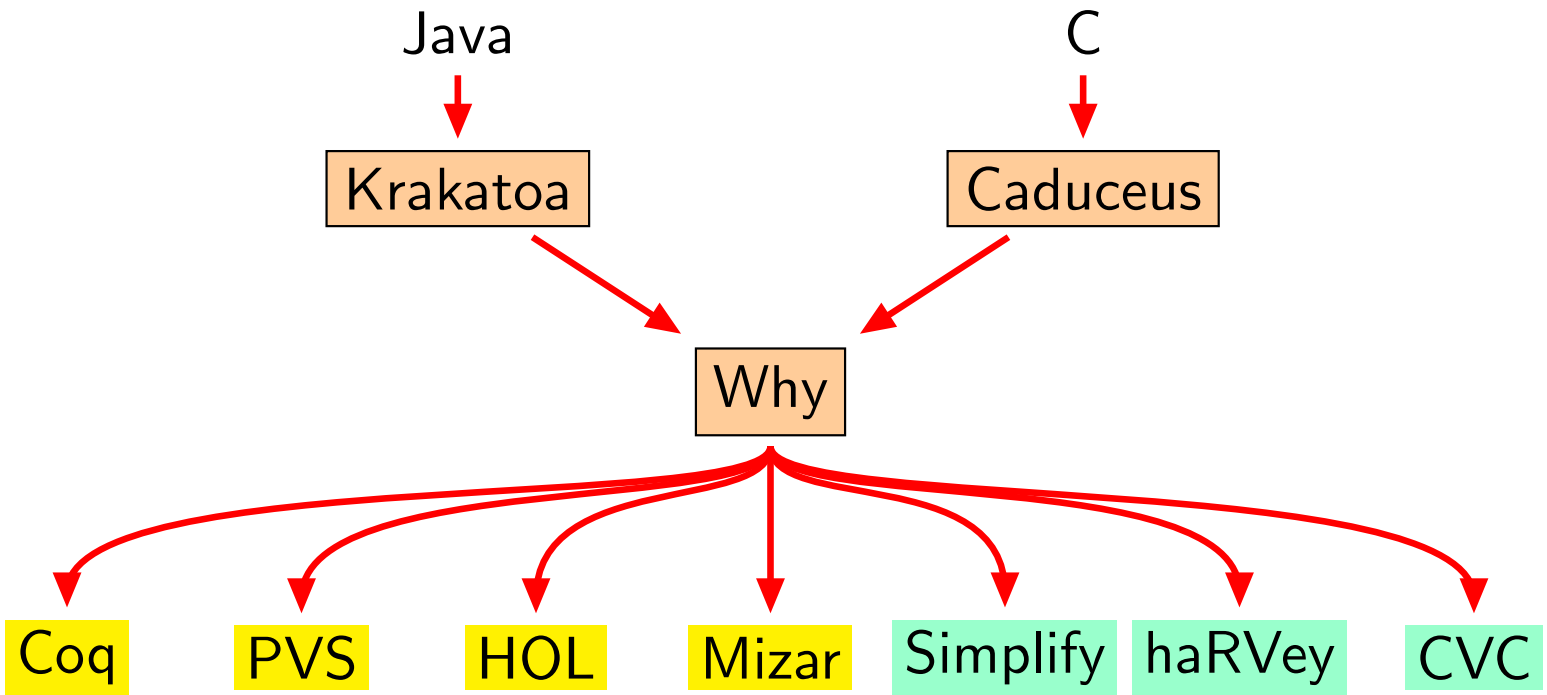

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1. The Why tool
   - Hoare logic revisited
   - Interpretation of imperative programs in Type Theory
   - Monads and effects
2. Verifying C and Java programs
   - Illustration on examples
   - Finding an adequate memory model
3. Perspectives
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Part I

The Why tool

Capture the essence of Hoare logic

1. absence of aliasing
2. embedding of the logic inside the programming language

$$\{\ P[x \leftarrow E]\ \}\ x\ :=\ E\ \{\ P\ \}$$

We look for

- as much genericity as possible
  (w.r.t. input language / logic / back-end provers)
- a safe method (not yet another VCG)

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Key idea

Translate an imperative program into Type Theory using monads

From a program $\{P\}\ p\ \{Q\}$, build a proof

$$\hat{p} : \forall x_1, \ldots, x_n.\ P \Rightarrow \exists y_1, \ldots, y_m.\ Q$$

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Example

to establish

$$\{x \geq 0\}\ x\ :=\ !x + 1\ \{x > 0\}$$

we build a proof of

$$\forall x_0.\ x_0 \geq 0 \Rightarrow \exists x_1.\ x_1 > 0$$

which is

$$\lambda x_0.\ \lambda P : x_0 \geq 0.\ \text{let } x_1 = x_0 + 1 \text{ in } (\text{exists } x_1\ (? : x_1 > 0))$$

resulting in one obligation

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\begin{array}{rcl}
e & ::= & c \mid x \mid \mathsf{fun}\ x : \tau \to e \mid e\ e \mid !x \mid x := e \mid \mathsf{ref}\ e \\
& \mid & \mathsf{if}\ e\ \mathsf{then}\ e\ \mathsf{else}\ e \mid \mathsf{let}\ x = e\ \mathsf{in}\ e \mid \mathsf{rec}\ f\ (\vec{x} : \vec{\tau}) : \tau = e \\
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derived constructs:

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e_1; e_2 \equiv \mathsf{let}\ \_ = e_1\ \mathsf{in}\ e_2
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the postcondition Q may mention $!x$, $!\overleftarrow{x}$ and *result*

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Typing with effects

In an environment $\Gamma = x_1 : \tau_1, \ldots, x_n : \tau_n$ of values we infer the type with effects of a program e

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In particular, typing

- forbids aliasing
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Interpretation in CIC

A program e of type $\kappa = (P, \tau, \epsilon, Q)$ where $\epsilon =$ reads $\vec{x}$ writes $\vec{y}$ is interpreted in CIC as

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Soundness

We define an operational semantics for our programs (following Wright and Felleisen's *A syntactic approach to type soundness*)
$\theta.e \mapsto^\star \theta'.v$

First we show that the computational part of $\hat{e}$ respects the semantics of e

$$\exists \theta', v.\, \theta.e \mapsto^\star \theta'.v \iff (\overline{e}\,\theta(x_1)\ldots\theta_n(x_n)) = (\theta'(y_1), \ldots, \theta'(y_m), v)$$

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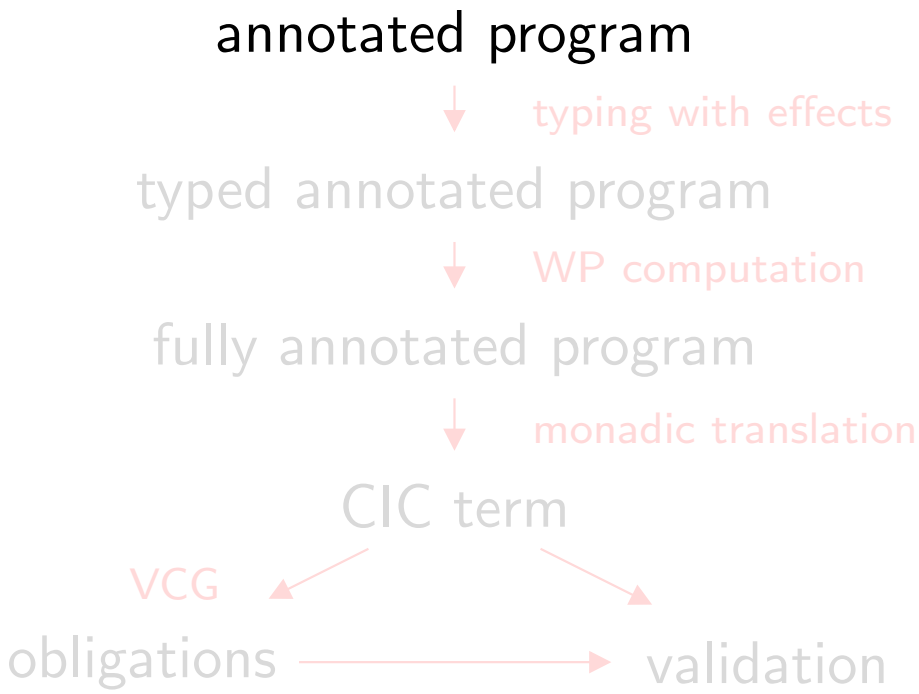

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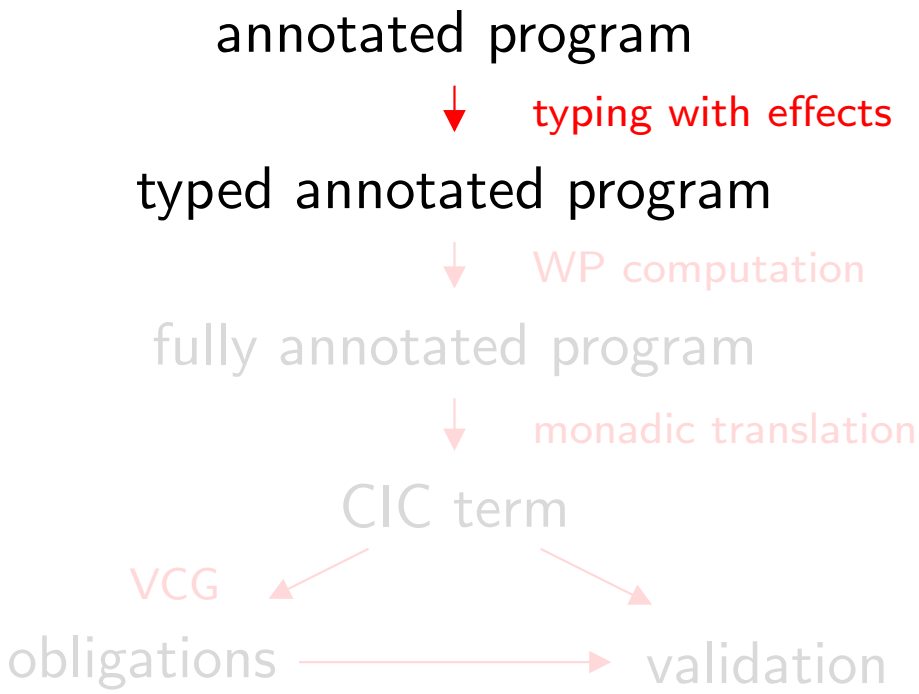

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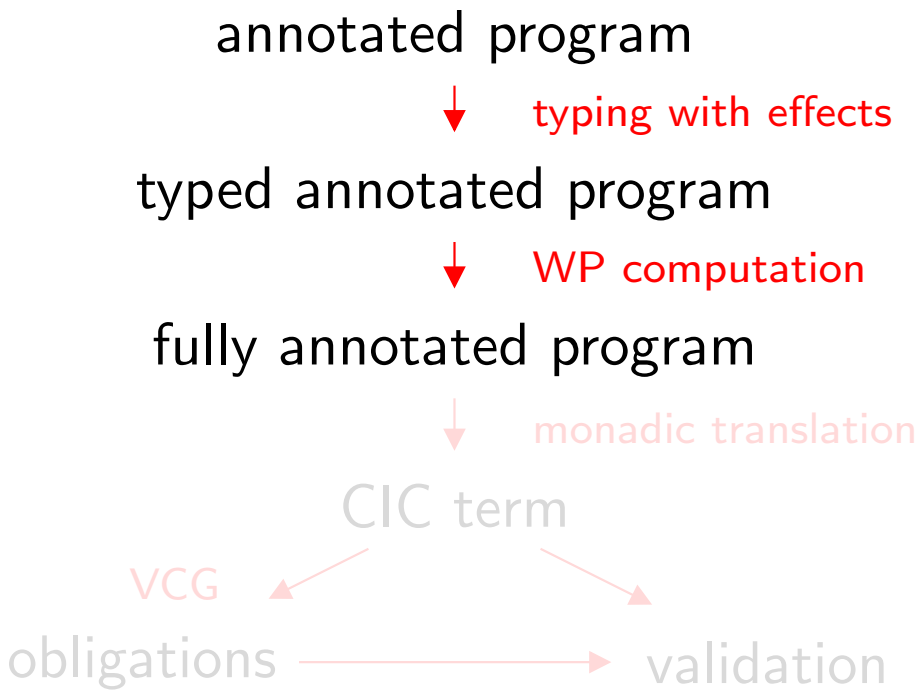

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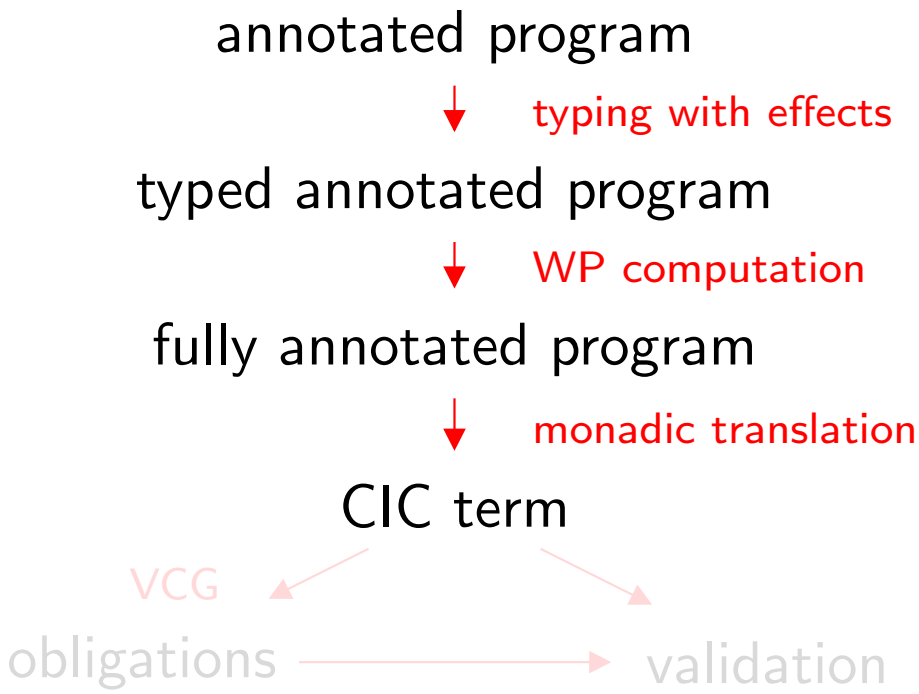

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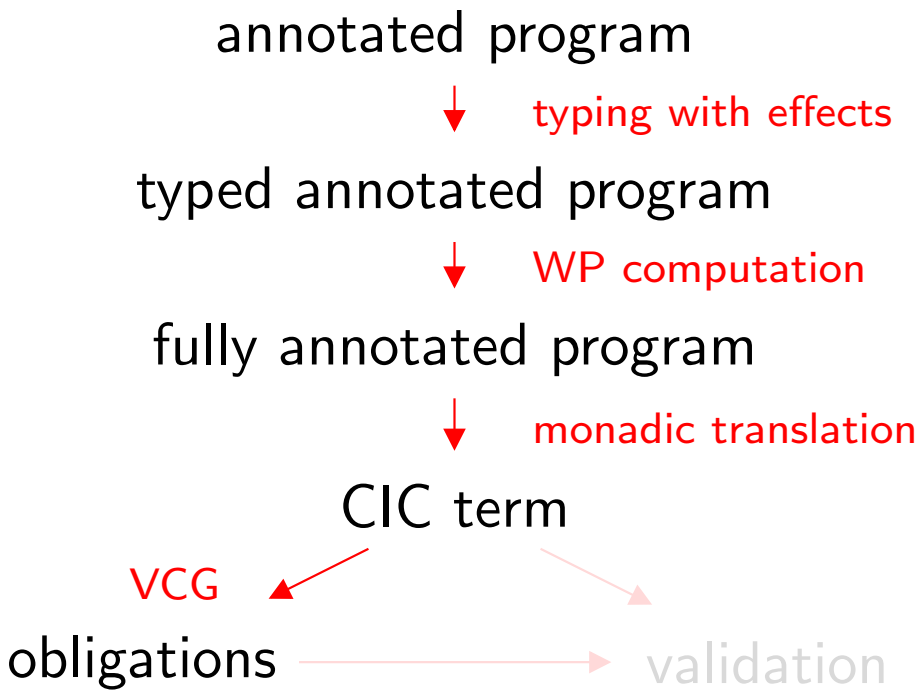

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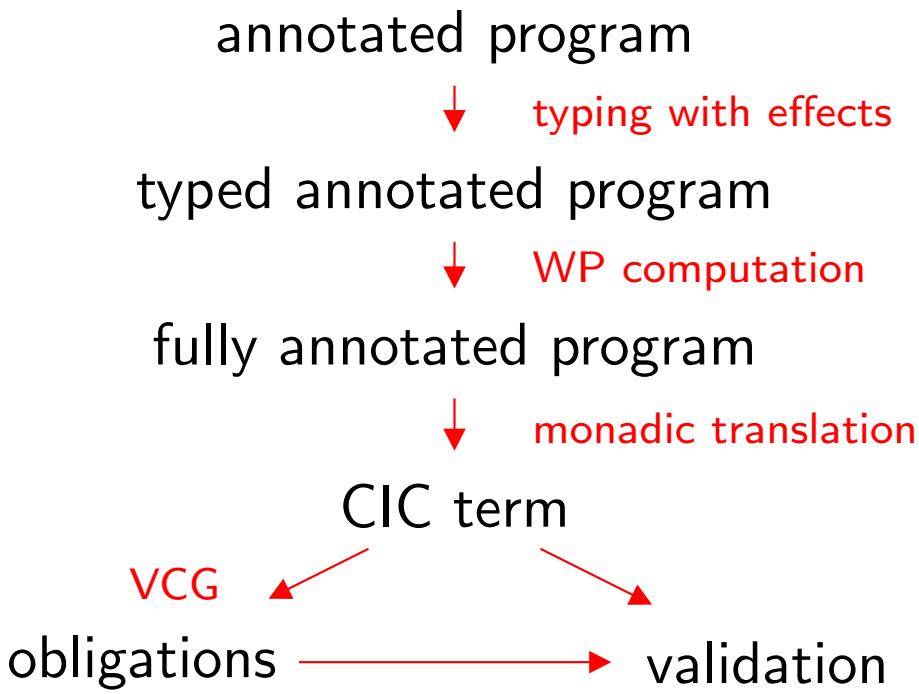

The Why tool in practice

The tool includes additional features

- exceptions
  - $e ::= \ldots \mid \text{raise } (E\ e) \mid \text{try } e \text{ with } E\ x \Rightarrow e$
  - $\epsilon ::= \text{reads } \vec{x} \text{ writes } \vec{x} \text{ raises } \vec{E}$
  - postcondition $Q; E_1 \Rightarrow Q_1; \ldots; E_n \Rightarrow Q_n$
- modularity
  one can declare types / logic functions / predicates / programs
- polymorphism
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Logic

Annotations are not written in CIC but in a logical subset common to a maximal set of provers

polymorphic multi-sorted first-order logic
(with equality and arithmetic)

actually, we only need

- to embed logical terms inside programs
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Example

```
type 'a array

logic length : 'a array -> int
logic acc : 'a array, int -> 'a
logic upd : 'a array, int, 'a -> 'a array

parameter get : t:'a array ref -> i:int ->
   { 0 <= i < length(t) } 'a reads t { result = acc(t, i) }

parameter set : t:'a array ref -> i:int -> v:'a ->
   { 0 <= i < length(t) } unit writes t { t = upd(t@, i, v) }
```

Example (cont'd)

```
exception Found of int
exception Not_found

let search (t : int array ref) =
  {}
  try
    let i = ref 0 in begin
    while !i < (length !t) do
      { invariant 0 <= i and forall k:int. 0 <= k < i -> acc(t,k) <> 0
        variant length(t) - i }
      if (get t !i) = 0 then raise (Found !i);
      i := !i + 1
    done;
    raise Not_found : int
    end
  with Found x ->
    x
  end
  { acc(t, result) = 0
  | Not_found => forall k:int. 0 <= k < length(t) -> acc(t,k) <> 0 }
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Example (cont'd)

We get the usual Hoare logic proof obligations:

1. loop invariant holds initially
2. precondition of `(get t !i)`
3. preservation of the loop invariant
4. decreasing of the variant (termination)
5. final postcondition when terminating normally
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all of them are automatically discharged by Simplify

Note: we can still type-check the validation (with Coq)

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Part II

Verifying C and Java programs

We propose a new approach for the verification of Java and C programs and two tools

- Krakatoa: verification of Java programs
  - specified using JML (Java Modeling Language)
- Caduceus: verification of C programs
  - specification language à la JML

Both are currently under experimentation on industrial code (Axalto / Dassault Aviation)

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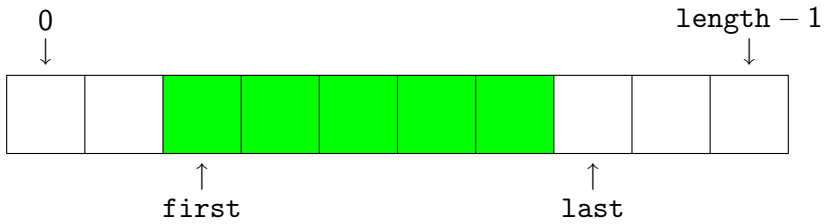
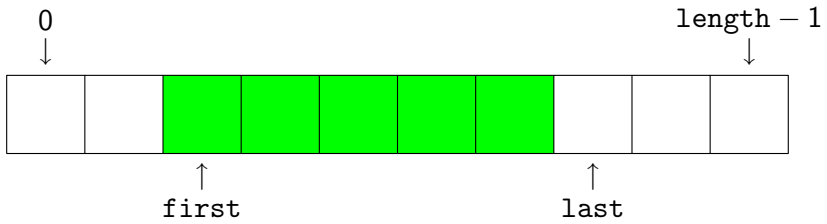
Example: character queue as circular array




```
struct queue {
  char contents[];
  int length;
  int first, last;
  unsigned int empty, full :1;
} q;
/*@ invariant q_invariant :
  @   \valid_range(q.contents, 0, q.length-1) &&
  @   0 <= q.first < q.length &&
  @   0 <= q.last < q.length
  @*/
```

Example: character queue as circular array




```
struct queue {
  char contents[];
  int length;
  int first, last;
  unsigned int empty, full :1;
} q;
```

```
/*@ invariant q_invariant :
  @   \valid_range(q.contents, 0, q.length-1) &&
  @   0 <= q.first < q.length &&
  @   0 <= q.last < q.length
  @*/
```

Example continued: specifying functions

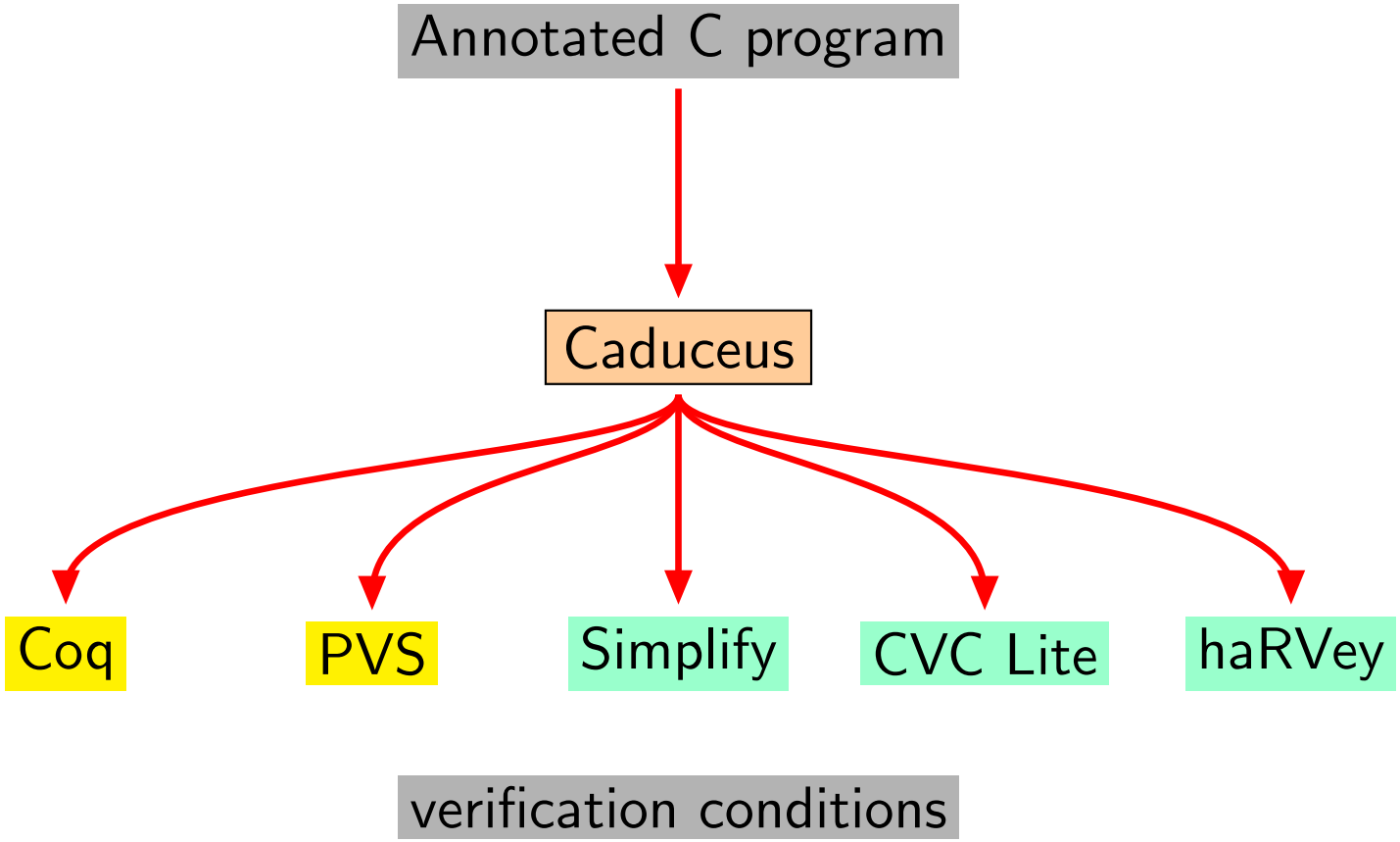
```
/*@ requires !q.full
  @ assigns  q.empty, q.full, q.last, q.contents[q.last]
  @ ensures  !q.empty && q.contents[\old(q.last)] == c
  @*/
void push(char c);

/*@ requires !q.empty
  @ assigns q.empty, q.full, q.first
  @ ensures !q.full && \result == q.contents[\old(q.first)]
  @*/
char pop();
```

Example continued: body for push function

```
/*@ requires !q.full
  @ assigns  q.empty, q.full, q.last, q.contents[q.last]
  @ ensures  !q.empty && q.contents[\old(q.last)] == c
  @*/
void push(char c) {
  q.contents[q.last++] = c;      // insert 'c' in the queue
  if (q.last == q.length)
        q.last = 0;              // wrap if needed
  q.empty = 0;                   // queue is not empty
  q.full = (q.first == q.last); // queue is full if
                                 // 'last' reaches 'first'
}
```

Multi-prover architecture



Example continued: certification of `push` function

Caduceus produces 3 verification conditions expressing that

- the code of `push` contains no unallocated pointer dereference (e.g. assignment of `q.contents[q.last++]` is valid)
- the postcondition and the `assigns` clause of `push` are established
- the invariant `q_invariant` is preserved by `push`

Proofs of these obligations

- with Simplify (100%) and CVC Lite (67%)
- with Coq (100%), very easy (6 lines of tactics)

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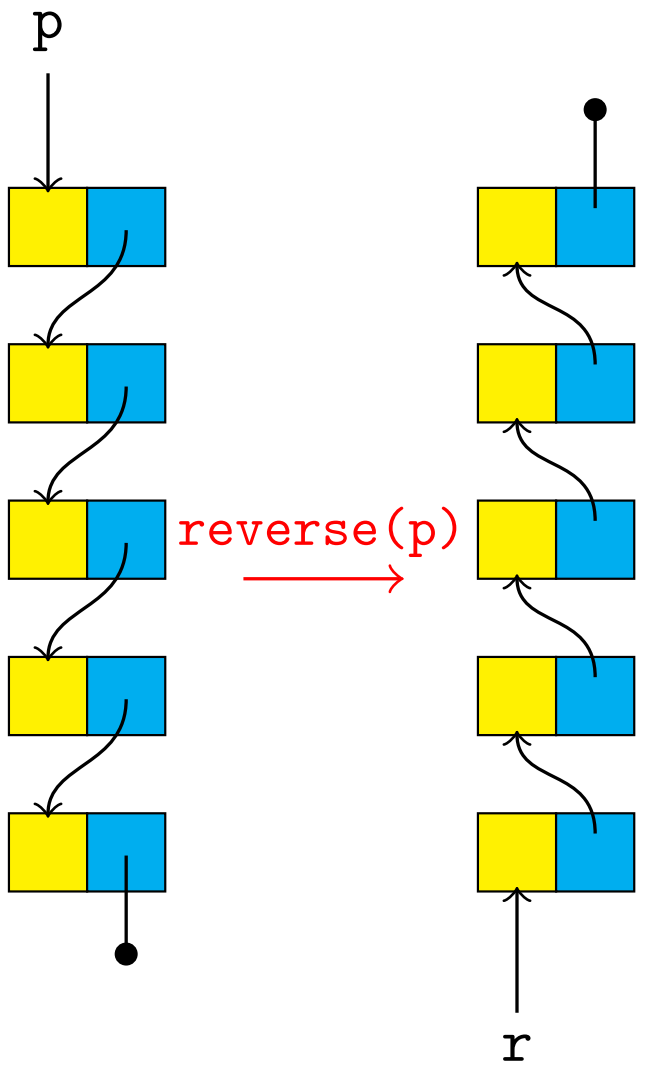
Example: in-place list reversal

```
typedef struct struct_list {
  int hd;
  struct struct_list *tl;
} *list;

list reverse(list p) {
  list r = NULL;
  while (p != NULL) {
    list q = p ;
    p = p->tl;
    q->tl = r;
    r = q;
  }
  return r;
}
```



Introduction of new logical types and functions

- New predicates and functions can be introduced

```
// logical finite list of pointers
//@ logic plist nil()
//@ logic plist cons(list p, plist l)

// concatenation and reversal
//@ logic plist app(plist l1, plist l2)
//@ logic plist rev(plist pl)
```

- Axioms may be given, e.g.

```
//@ axiom app_nil : \forall plist l; app(nil(),l) == l
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Specification of list reversal

```
/* llist(p,l) specifies that l is the list of pointers
   from p to NULL following tl fields */
//@ predicate llist(list p, plist l) reads p->tl

// is_list(p) specifies that p is finite
//@ predicate is_list(list p) { \exists plist l ; llist(p,l) }

/*@ requires is_list(p)
  @ ensures \forall plist l;
  @    \old(llist(p, l)) => llist(\result, rev(l))  */
list reverse(list p);
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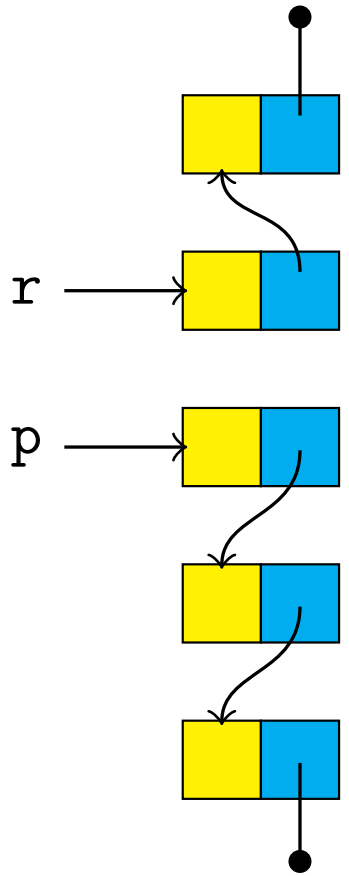
Annotating the code of list reversal

```
list reverse(list p) {
  list r = NULL;
/*@ invariant
    \exists plist lp; \exists plist lr;
      llist(p, lp) && llist(r, lr) &&
      disjoint(lp, lr) &&
      \forall plist l; \old(llist(p, l)) =>
        app(rev(lp), lr) == rev(l)
   @ variant length(p) for length_order */
  while (p != NULL) {
    list q = p;
    p = p->tl; q->tl = r; r = q;
  }
  return r;
}
```



Certification of list reversal

- 7 verification conditions
- With Simplify: 71%
- With Coq: 100%, with 661 lines of tactics

Example: Schorr-Waite algorithm

- Graph marking algorithm
- Considered as a benchmark for the verification of pointer programs (Bornat, 1999, Jape system) (Nipkow-Mehta, 2003, Isabelle/HOL)
- 12 verification conditions
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Underlying technique

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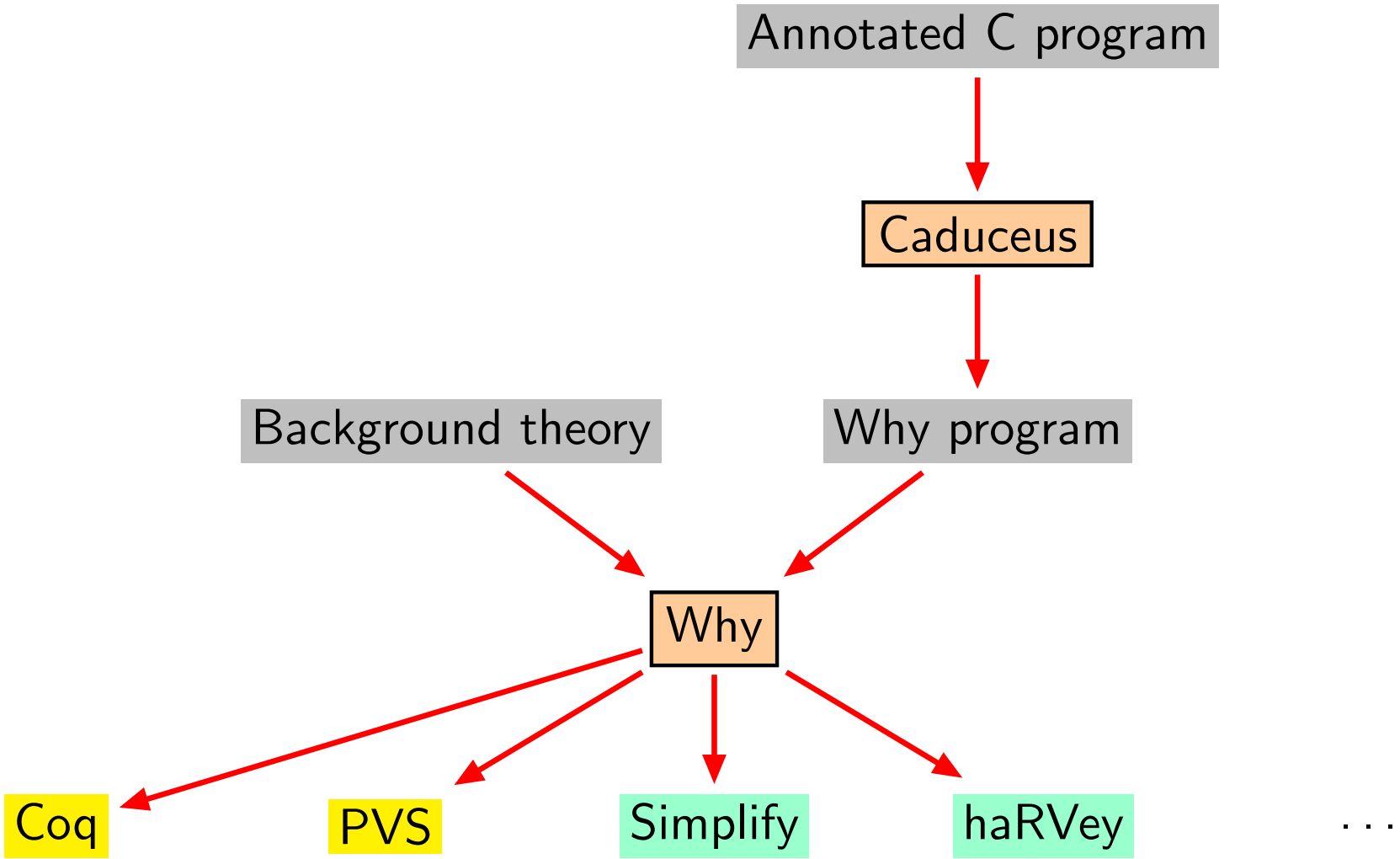

Modeling C memory heap

- Burstall-Bornat model: memory partition according to structure fields
- We extend this idea to handle C arrays and pointer arithmetic: a memory block is

- Each structure field is a map from addresses to memory blocks

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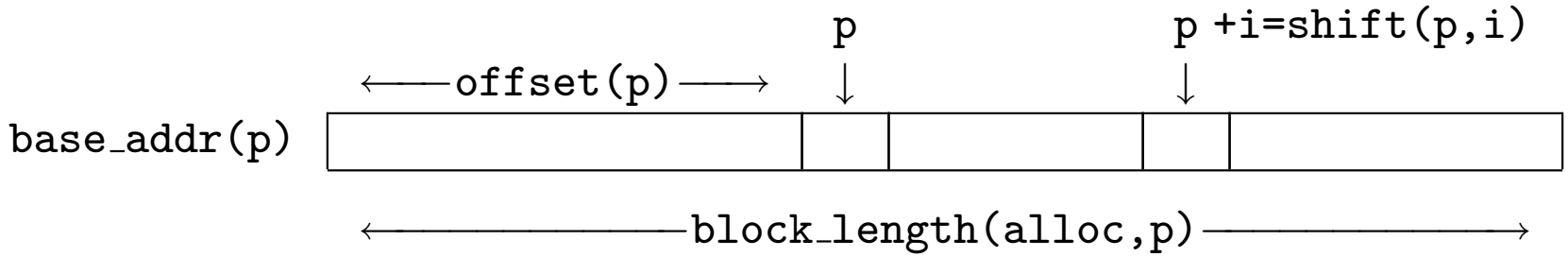

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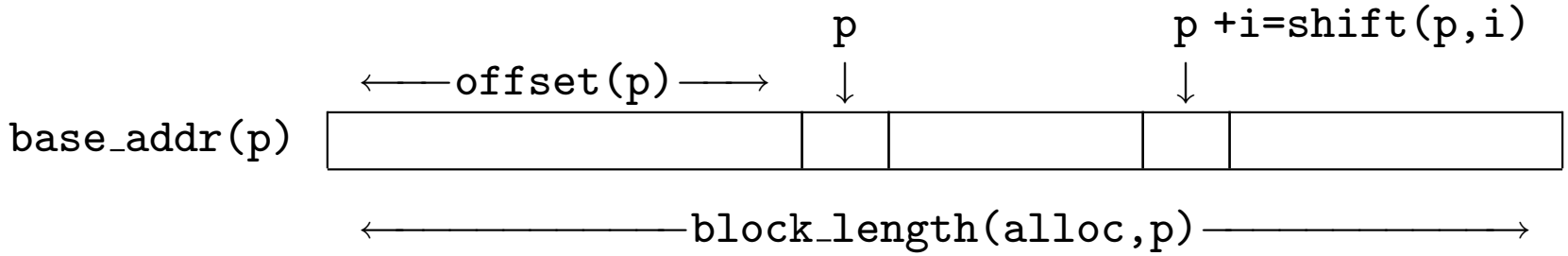

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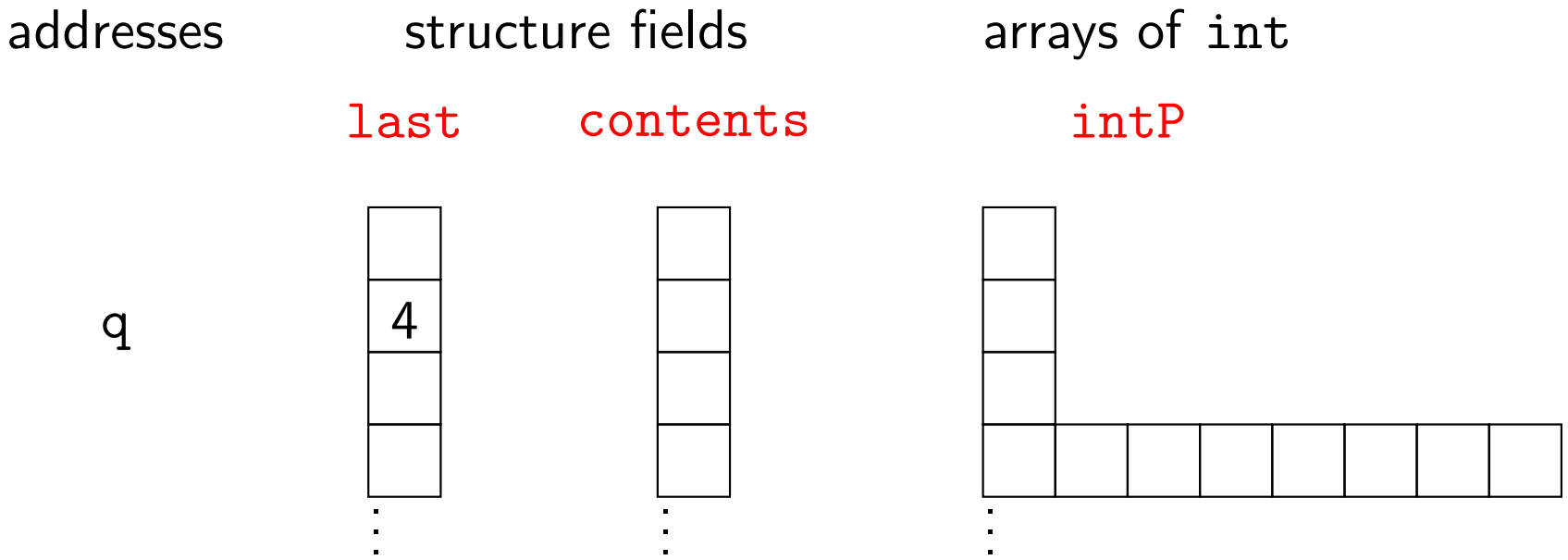
Burstall-Bornat model: example of character queue

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q.contents[q.last++] = c
    q.last <- 4 + 1
    *(q.contents+4) <- c
```

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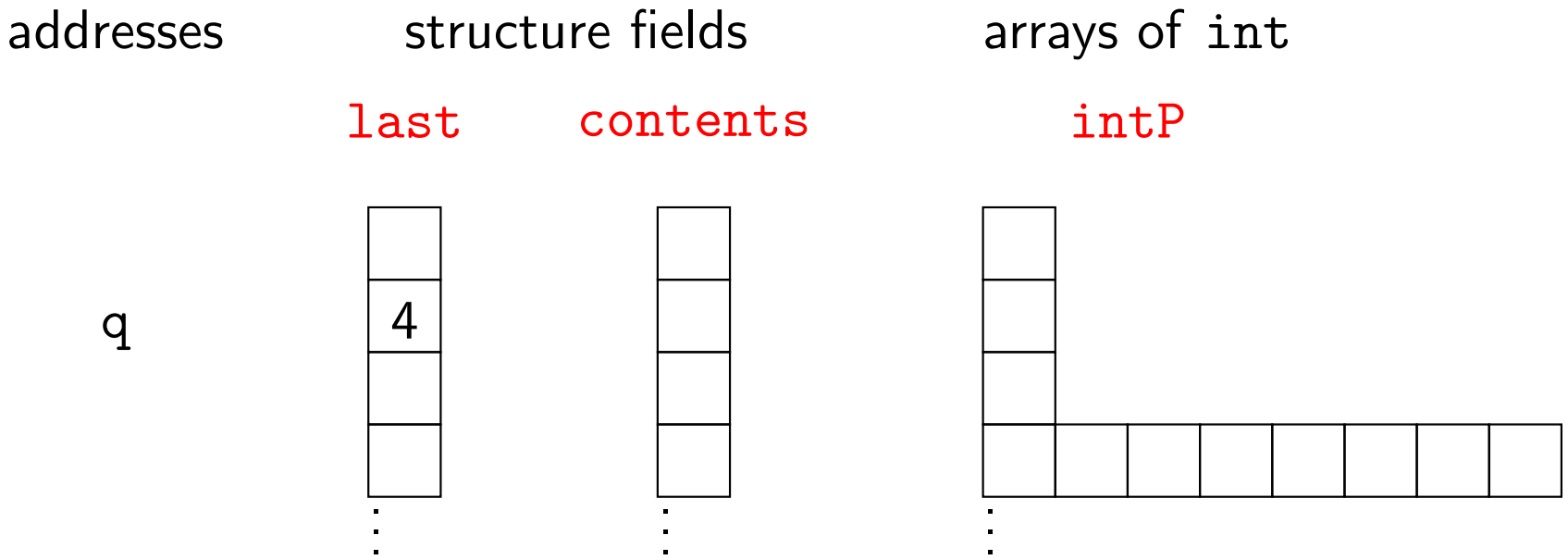


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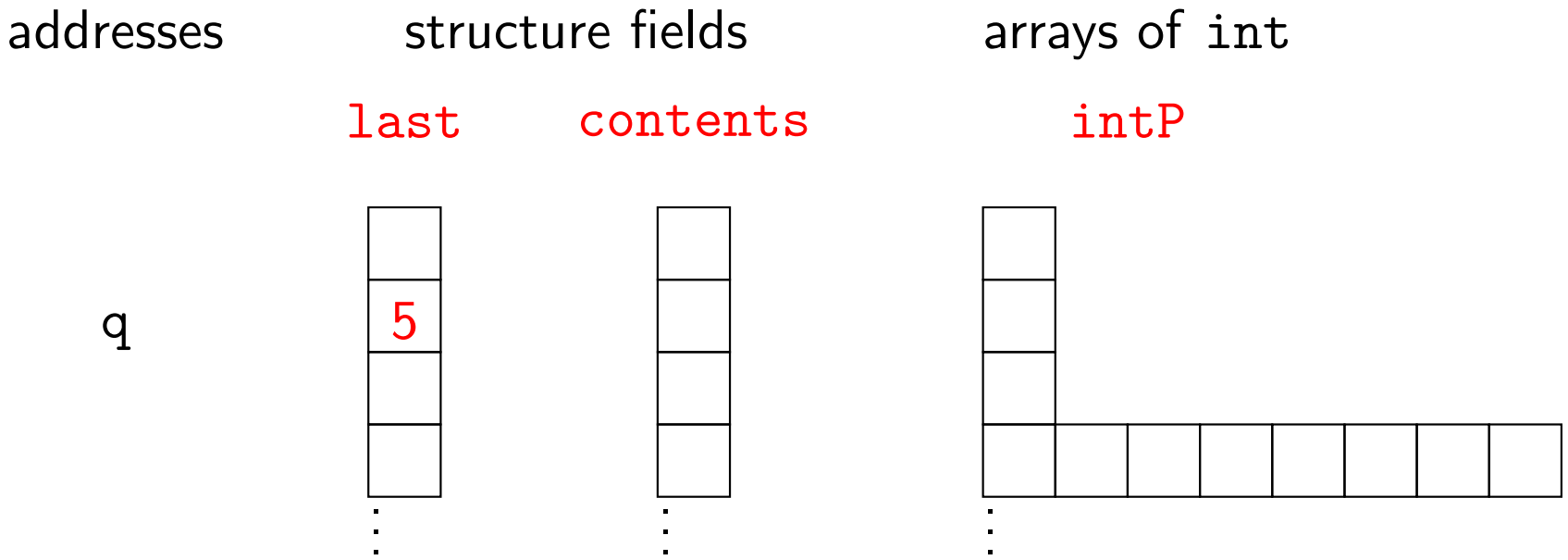


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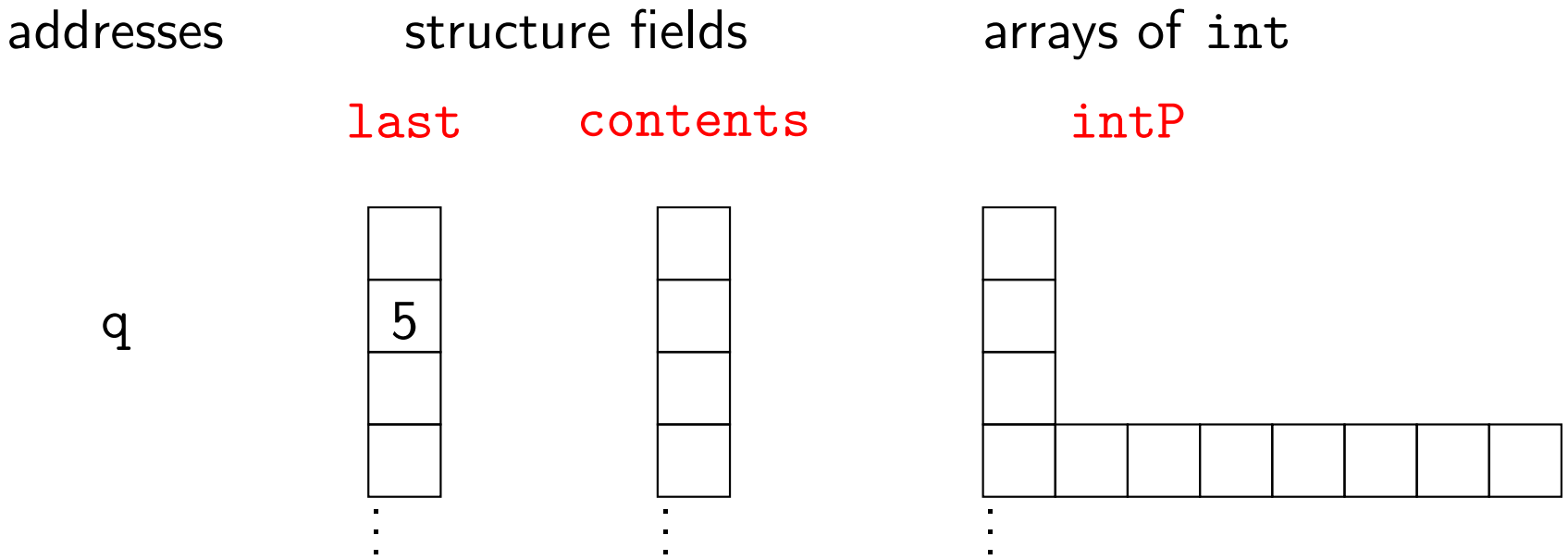


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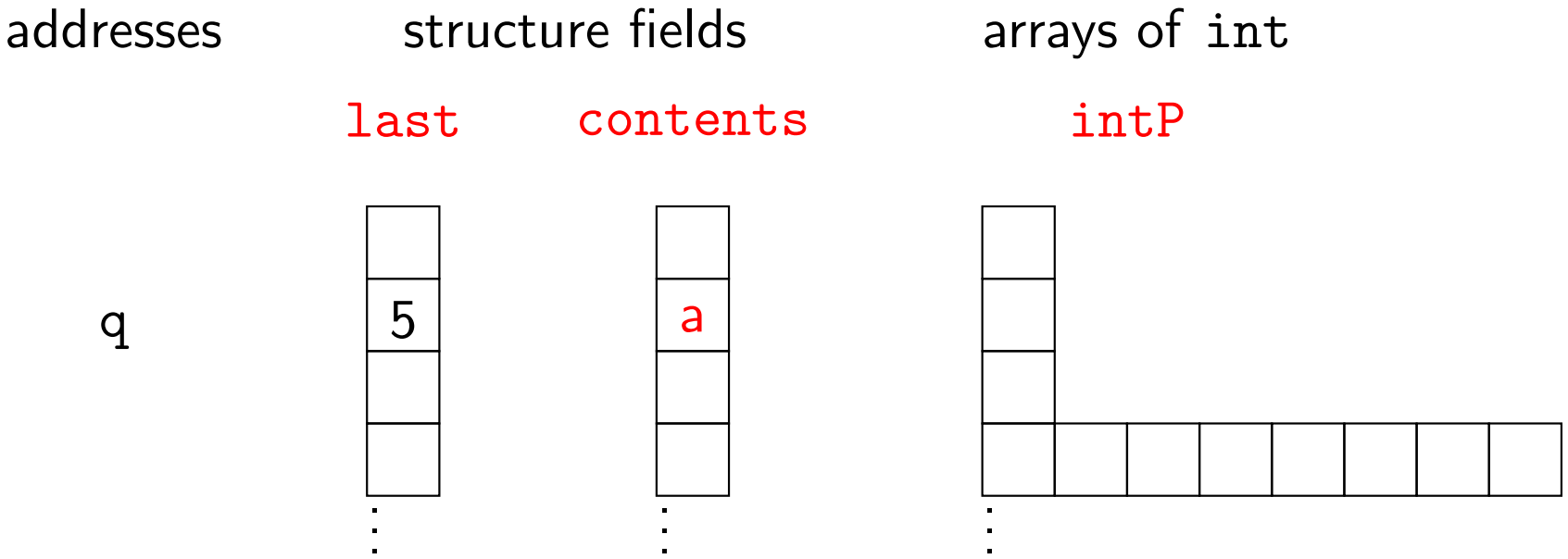


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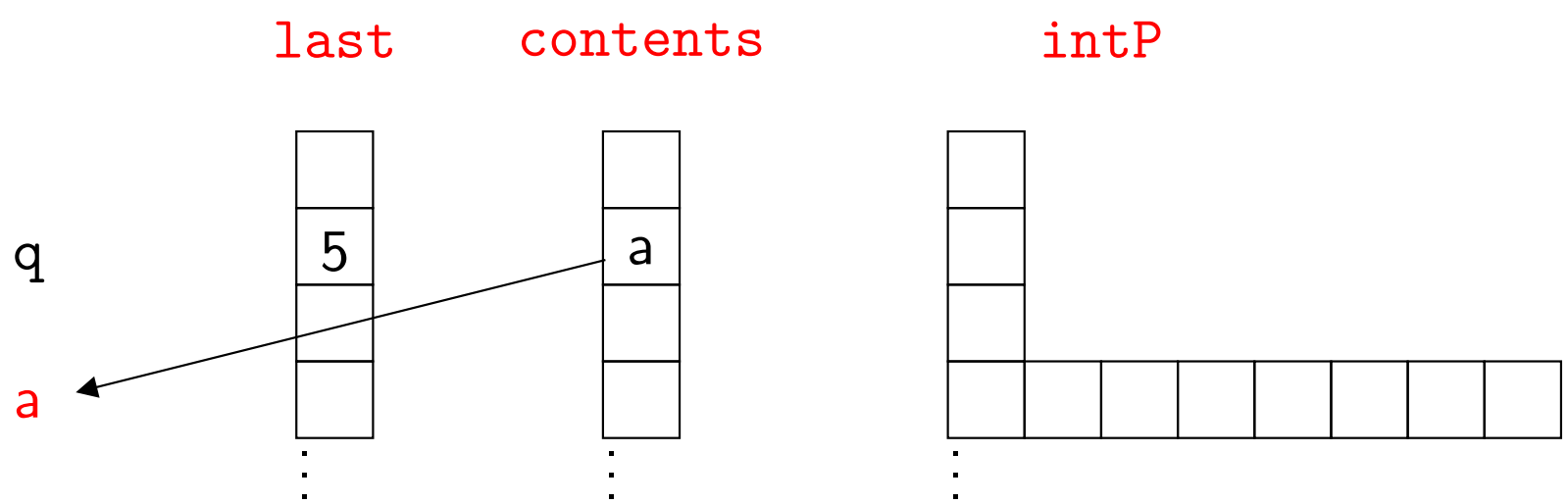
Burstall-Bornat model: example of character queue

addresses structure fields arrays of `int`

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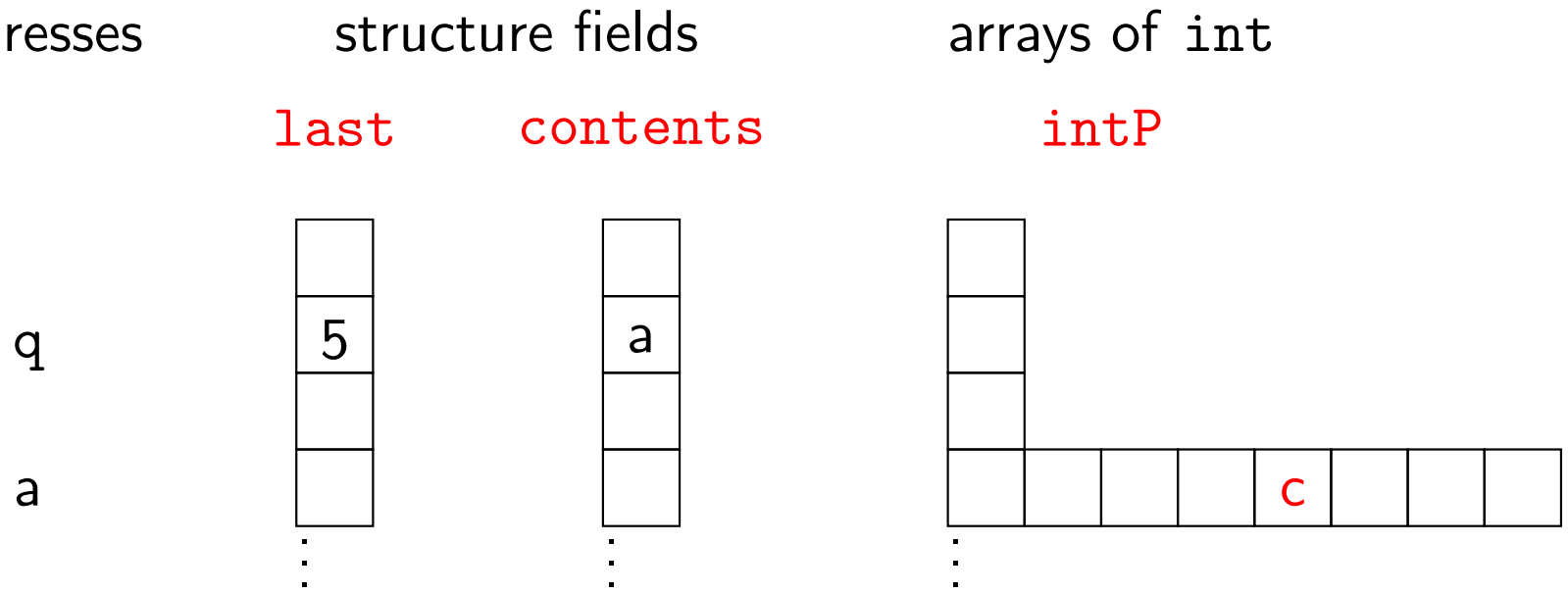


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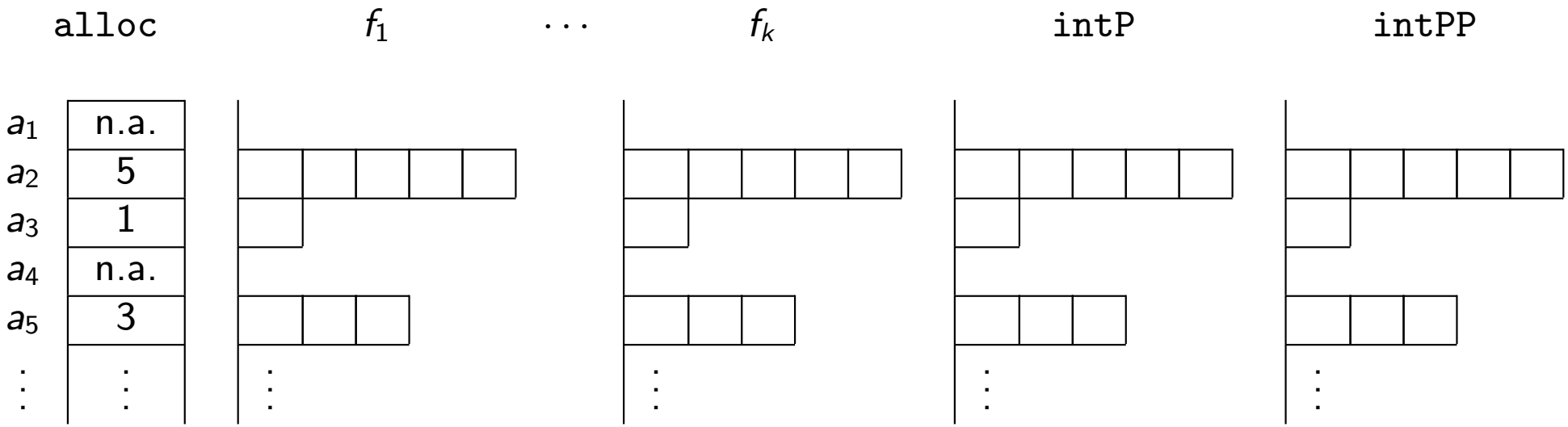
General structure of C memory heap



Translation of C statements into Why

The C statement

```
q.contents[q.last++] = c
```

becomes in Why:

```
assert valid(!alloc,q);          // proof obligation
let tmp1 = acc(!last,q) in       // tmp1 <- q.last
last := upd(!last,q,tmp1+1);     // q.last <- tmp1+1
let tmp2 = shift(acc(!contents,q),tmp1) in
                                 // tmp2 <- q.contents + tmp1
assert valid(!alloc,tmp2);       // proof obligation
intP := upd(!intP,tmp2,c)        // *tmp2 <- c
```

Axiomatization

- The abstract Why functions `acc`, `upd`, `shift`, etc. are specified by axioms: the background theory
- Excerpt from this theory:

```
acc(upd(t,i,v),i) = v
i <> j -> acc(upd(t,i,v),j) = acc(t,j)
shift(p,0) = p
shift(shift(p,i),j) = shift(p,i+j)
...
```

- An important part of this theory is dedicated to assigns clauses

Soundness

Soundness of the translation not formally proved, but

- based on the Why tool, which is sound
  - the Why validation can be type-checked
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Same methodology, with a very similar model

- one map for each class attribute
- a pointer is valid if it is not `null` (no pointer arithmetic)

But the JML sometimes lacks a precise semantics

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Part III

Conclusion and perspectives

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- We support a large subset of ANSI C and Java/JML
- Prototypes freely available
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- arithmetic overflow
- floating point arithmetic
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The Burstall-Bornat model could apply (one map for each mutable structure field); includes references as a particular case

- `type 'a ref = { mutable contents : 'a }`

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