Séminaire EPITA

# Certifying cost annotations in compilers

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Post-doc at PPS — Paris 7

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## The CerCo project

**Certified Complexity**

3 years European project (FP7)

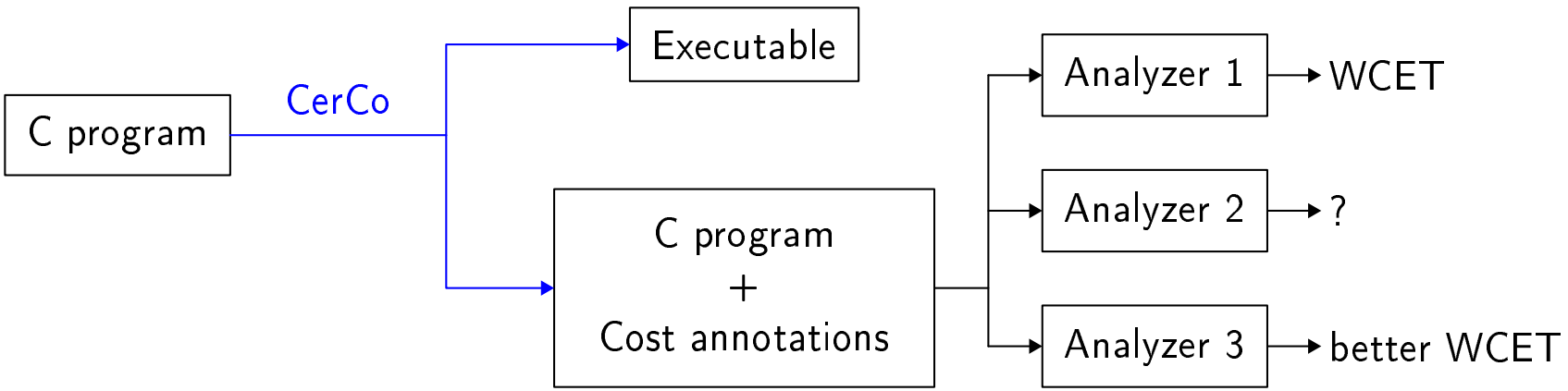
### Laboratories

- University of Bologna — Claudio Sacerdoti Cohen
- University of Edinburgh — Ian Stark
- **University of Paris Diderot (PPS)**

  Roberto Amadio (site leader)
  Yann Régis-Gianas
  Nicolas Ayache

# Goal

**Formally sound, cost annotating compiler**




✓ Overapproximated concrete complexity

# CerCo's approach: problematic

What is the cost of evaluating `tab[i]+1` ?

**Depends on:**

- The variable final locations
- The way memory accesses are compiled
- The way operations are compiled

$\Rightarrow$ Depends on the compilation process

# CerCo's approach: solution

## Bad solution

*Consider worst case scenarios*

- X Too imprecise
- X Optimizations lost
- X Not modular

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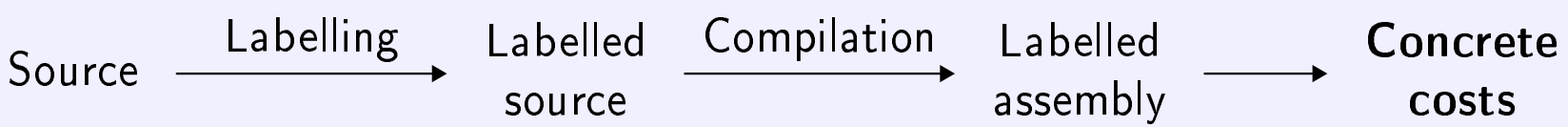
## CerCo's solution

*Symbolic cost update*: **label**



# CerCo's approach: common considerations

## Operational semantics

- *Without labels*: $\mathcal{P}(\text{Prog} \times \text{State} \times \text{State})$
- *With labels*: $\mathcal{P}(\text{Prog} \times \text{State} \times \text{label trace} \times \text{State})$

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## Annotation semantics

$\surd$ Annotation = Instruction of the source language

- Explicits cost annotations
- Analysis tools for cost synthesis

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Demo

# Outline

1. Toy compiler
   - Languages
   - Compilation
   - Labelling
   - Annotation
2. Realistic C compiler
   - Architecture
   - Labelling
3. Experiments
   - Cost synthesis
   - Lustre case study

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## Overview

$$\textbf{Imp} \longrightarrow \textbf{VM} \longrightarrow \textbf{ASM}$$

- **Imp**: simple while language
- **VM**: virtual machine (stack operations)
- **ASM**: assembly

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- **VM**: virtual machine (stack operations)
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**In the following...**

- How to label the languages?
- How to adapt the proofs?
- How to keep the proofs modular?

# Syntax

## Imp

$e ::= id \mid n \in \mathbb{N} \mid e + e \qquad b ::= e < e$
$S ::= \text{skip} \mid id := e \mid S\ ;\ S \mid \text{if } b \text{ then } S \text{ else } S \mid \text{while } b \text{ do } S$
$P ::= \text{prog } S$

## VM

$\mathcal{I} ::= \text{cnst}(n) \mid \text{var}(id) \mid \text{setvar}(id) \mid \text{add} \mid \text{branch}(k) \mid \text{bge}(k) \mid \text{halt}$
$P ::= \mathcal{I}\ \text{list}$

## ASM

$\mathcal{I} ::= \text{loadi } R,n \mid \text{load } R,addr \mid \text{store } R,addr \mid \text{add } R,R,R$
$\mid \text{branch } k \mid \text{bge } R,R,k \mid \text{halt}$
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# Labelled syntax

## $\text{Imp}^{\mathcal{L}}$

$e ::= id \mid n \in \mathbb{N} \mid e + e \qquad b ::= e < e$
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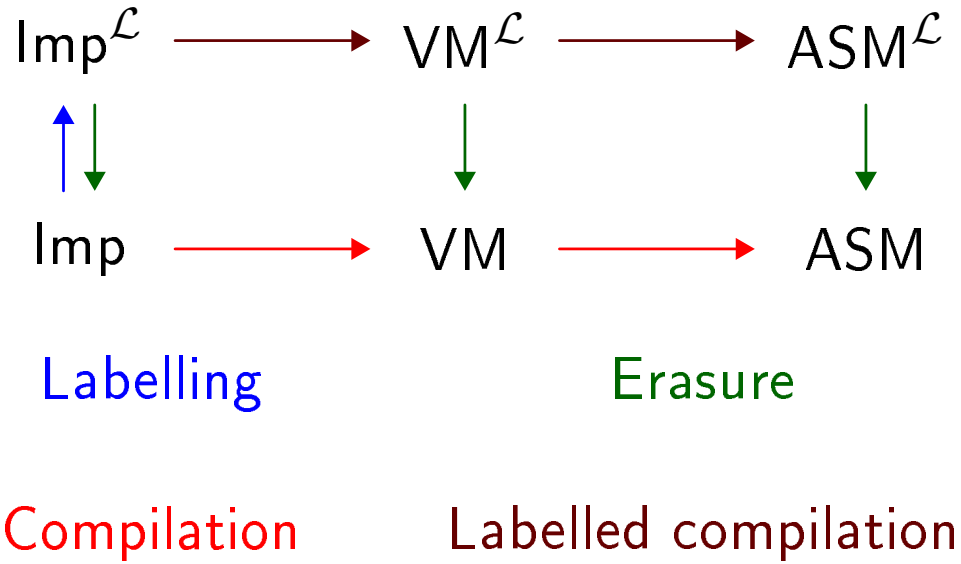
## Simulation


Imp$^{\mathcal{L}}$
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Imp
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Labelling
Erasure
Compilation
Labelled compilation

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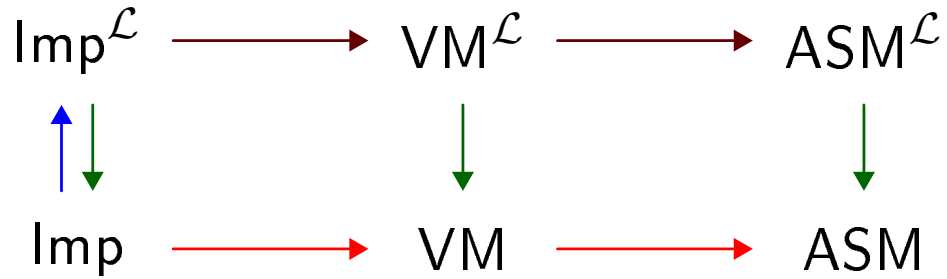



Labelling — Erasure

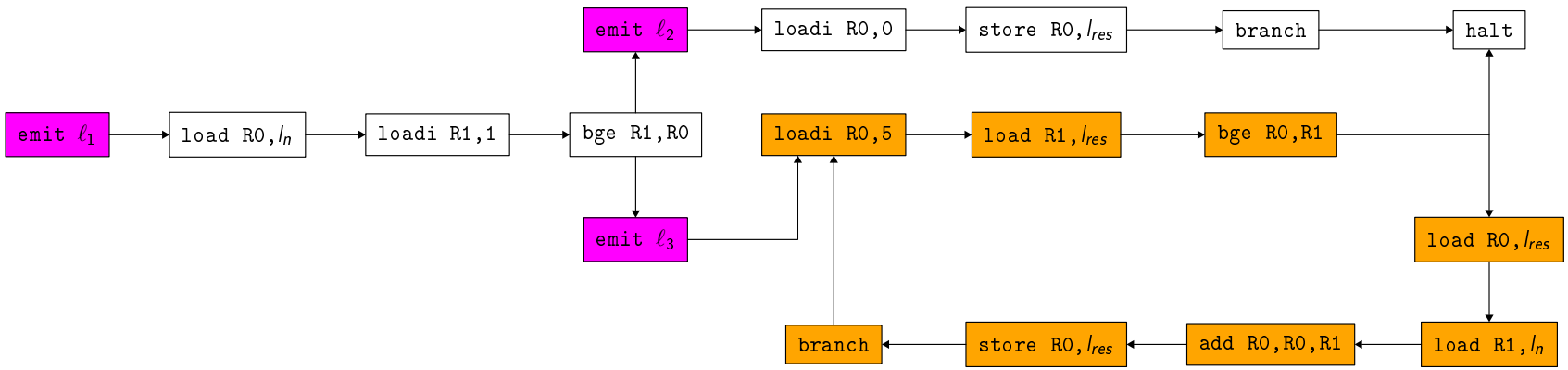
Compilation — Labelled compilation

**Theorem**: diagram commutativity

$$\left.\begin{array}{l} \mathcal{E}_{\mathsf{Imp}} \circ \mathcal{L}_{\mathsf{Imp}} = \mathsf{Id}_{\mathsf{Imp}} \\ \mathcal{C}_{\mathsf{Imp}} \circ \mathcal{E}_{\mathsf{Imp}} = \mathcal{E}_{\mathsf{VM}} \circ \mathcal{C}^{\mathcal{L}}_{\mathsf{Imp}} \\ \mathcal{C}_{\mathsf{VM}} \circ \mathcal{E}_{\mathsf{VM}} = \mathcal{E}_{\mathsf{ASM}} \circ \mathcal{C}^{\mathcal{L}}_{\mathsf{VM}} \end{array}\right\} \Rightarrow \mathcal{E}_{\mathsf{ASM}} \circ \mathcal{C}^{\mathcal{L}} \circ \mathcal{L}_{\mathsf{Imp}} = \mathcal{C}$$

# Example: soundness

```
prog
ℓ1:
if n < 1 then
  ℓ2:  res := 0
else
  ℓ3:
  while res < 5 do
        res := res + n
```



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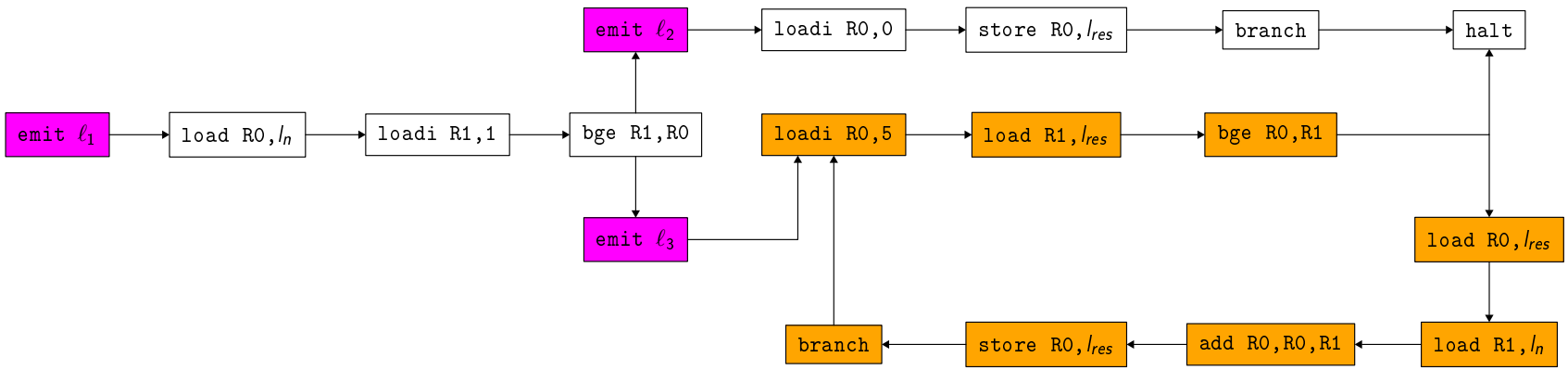
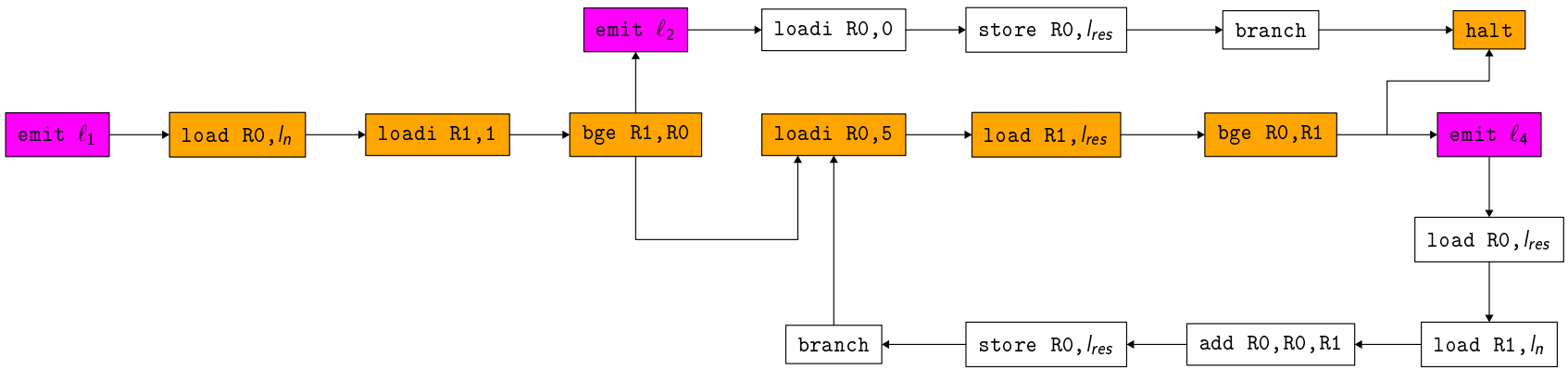



Loop with no label ⇒ not constant cost code

# Example: precision

```
prog
ℓ1:
if n < 1 then
  ℓ2:  res := 0
else

  while res < 5 do
    ℓ4:  res := res + n
```



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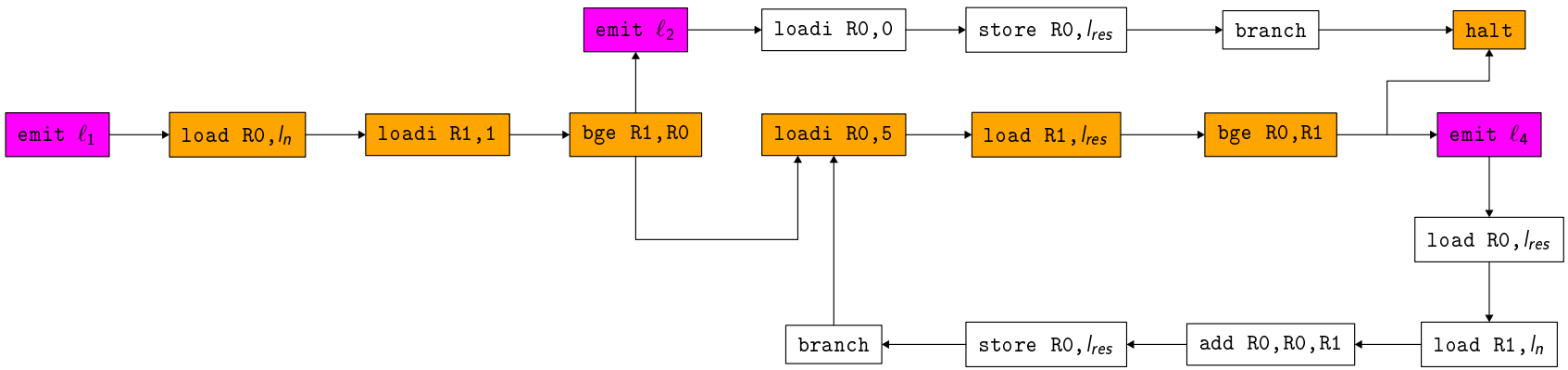


From emit $\ell_1$: three paths with different costs $\Rightarrow$ imprecision

# Labelling criteria

## Soundness

Every reachable code is in the scope of a label.
At least one label inside each loop.

## Precision

Two different paths to the next labels have the same cost.

## Criteria

The labelling must be **sound** and **precise**.
(This can be syntatically checked on the assembly code.)

√ Nice plus is a reasonable **economy**: not too many labels.

# Instrumentation

## Cost deduction

*Given:* $\phi$ : ASM Instruction list $\to \mathbb{N}$ $\left(\begin{array}{c}\text{loop free}\\ \text{may overapproximate}\end{array}\right)$

*Deduced:* $\kappa : \mathcal{L} \to \mathbb{N}$

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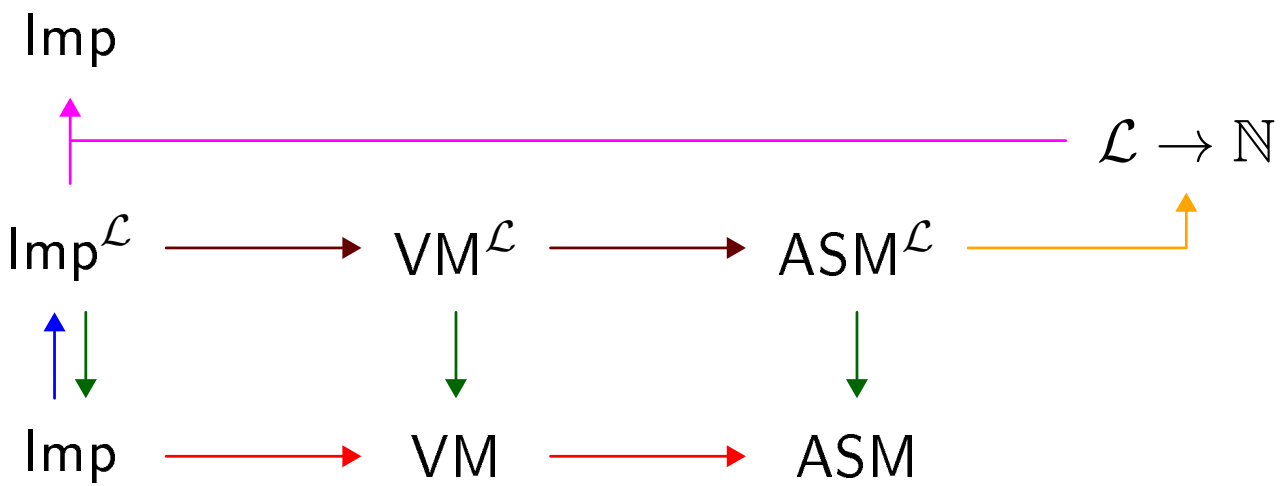
## Instrumentation

- Use a fresh variable
- Initialize it to 0
- Replace labels with increments (following $\kappa$)

```
prog                                prog
                                    _cost := 0;
ℓ1:                                 _cost := _cost + 2;
while res < 5 do          ⟶        while res < 5 do
  ℓ2:                                 _cost := _cost + 4;
  res := res + n                    res := res + n
```

# Annotation

**Annotation** = Instrumentation ∘ Labelling




Labelling

Erasure

Compilation

Labelled compilation

Cost deduction

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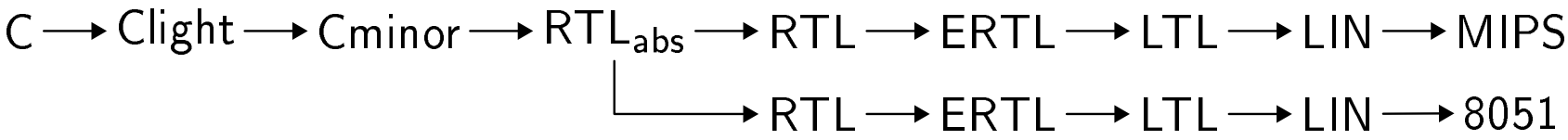



## C to Cminor

- Adapted from **CompCert**
  (GNU GPL and INRIA Non-Commercial)

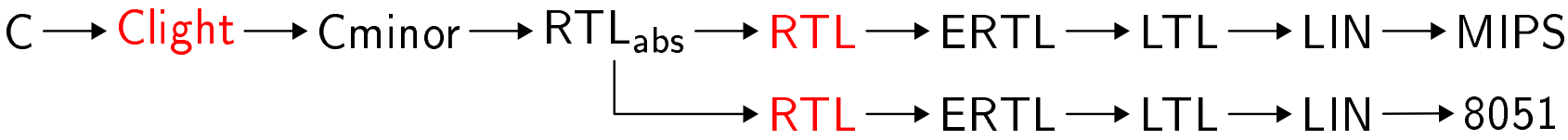
## RTL$_{abs}$

- Retargetting simplified
  - √ Some common optimizations
  - X Some optimizations lost

## Back-ends

- Adapted from pedagogical Pseudo-Pascal compiler
  (François Pottier, Creative Commons)

## Restrictions




Standalone files

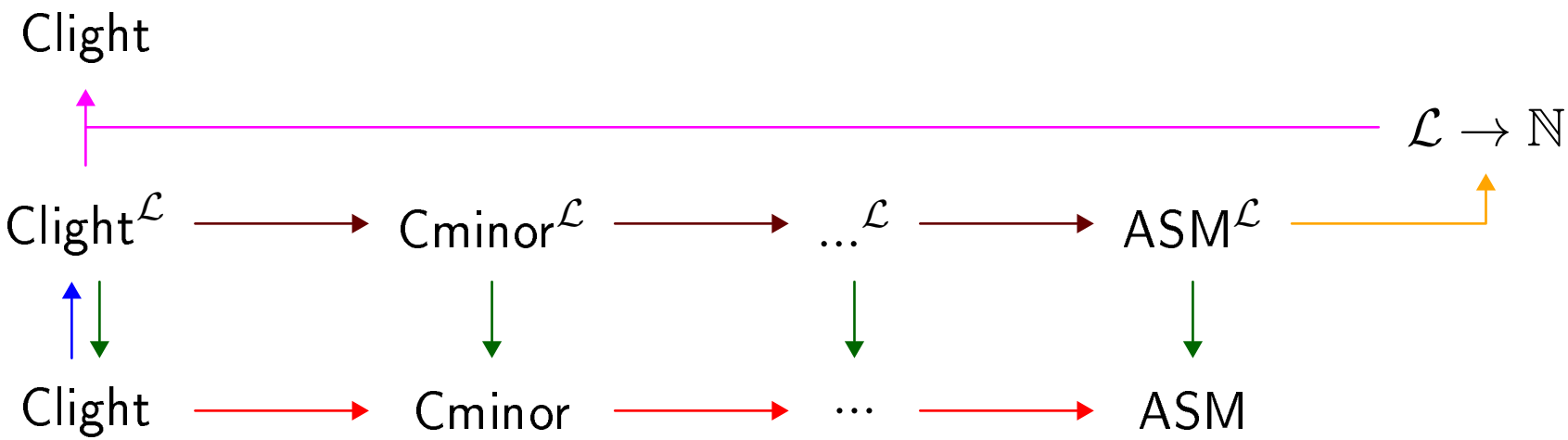
### Clight

- X `long long` and `long double` types
- X `longjmp` and `setjmp` instructions
- X Unreasonable forms of `switch`
- X Unprototyped and variable-arity functions

### RTL

- X `float`

# Overview

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## Differences Imp / C

**Side effect expressions** `y = x++;`

**Ternary expressions** `x ? y+2*z : z`

**Labels** and **Gotos** `lbl: ... goto lbl;`

**Function calls** `f(&x);`

# Differences Imp / C

**Side effect expressions** `y = x++;`

eliminated by CIL $\rightarrow$ `_tmp = x; x = _tmp+1; y = _tmp;`

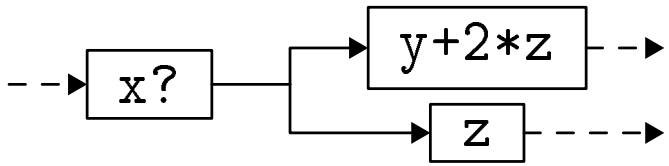
**Ternary expressions** `x ? y+2*z : z`

**Labels** and **Gotos** `lbl: ... goto lbl;`

**Function calls** `f(&x);`

# Ternary expressions

```
x?  (y+2*z) :  z
```




Branching ⇒ 1 label per branch for precision

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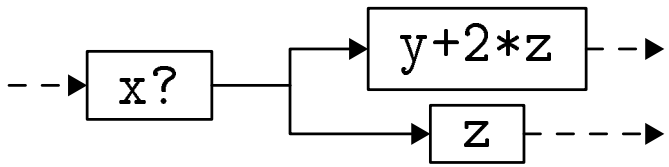



Branching $\Rightarrow$ 1 label per branch for precision

## Labelled expressions

```
x?  (ℓ1:  y+2*z) :  (ℓ2:  z)
```

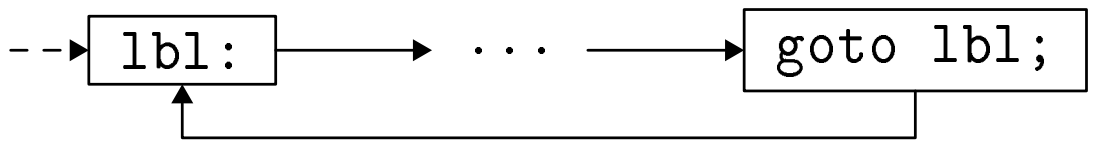
## Instrumentation

1) Side effects inside expressions  2) Elimination by CIL

C $\xrightarrow{\text{CIL}}$ Clight $\xrightarrow{\text{Instrument}}$ C $\xrightarrow{\text{CIL}}$ Clight

# Labels and Gotos

```
lbl:  ...  goto lbl;
```




Label ⇒ potential loop ⇒ 1 cost label needed

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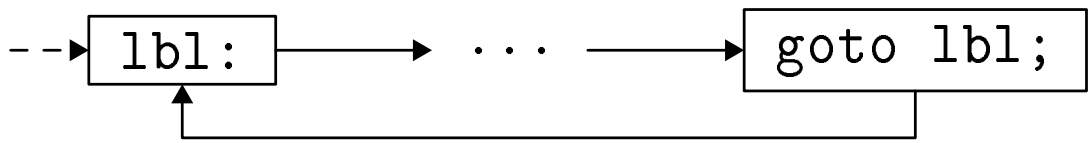


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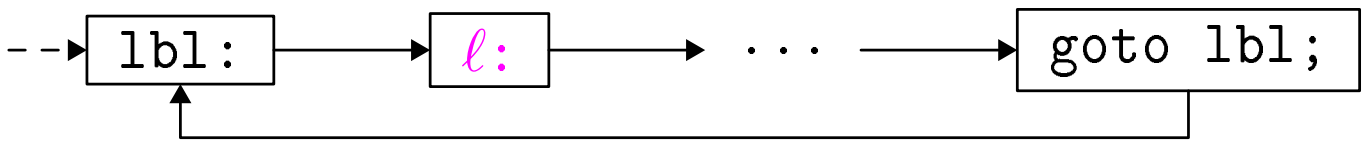
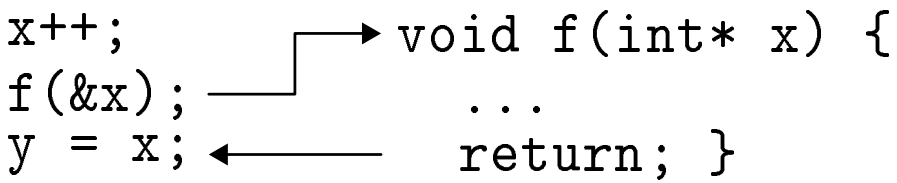


# Function calls

Function call: sequential instruction



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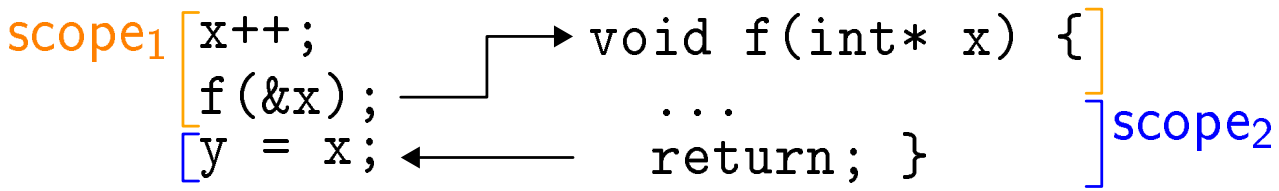

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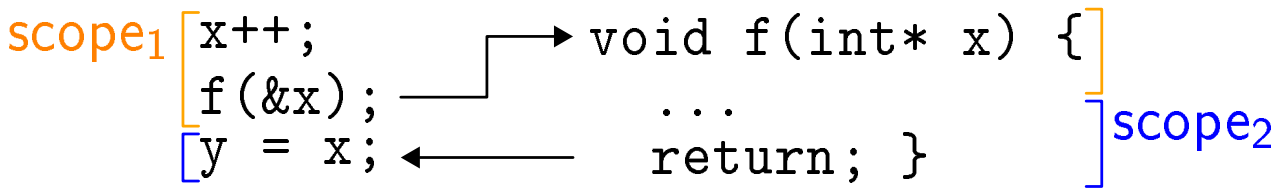
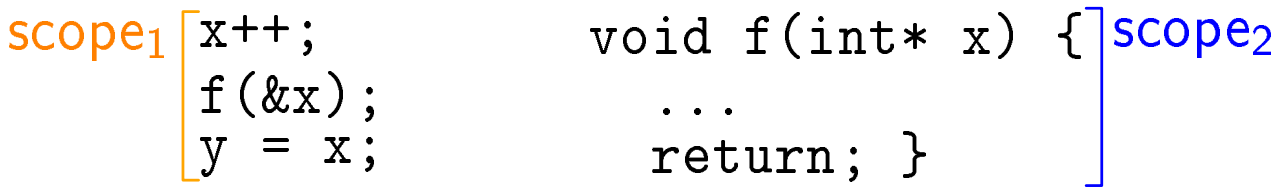



Function pointer: statically unresolvable destination

√ Each function handles its cost



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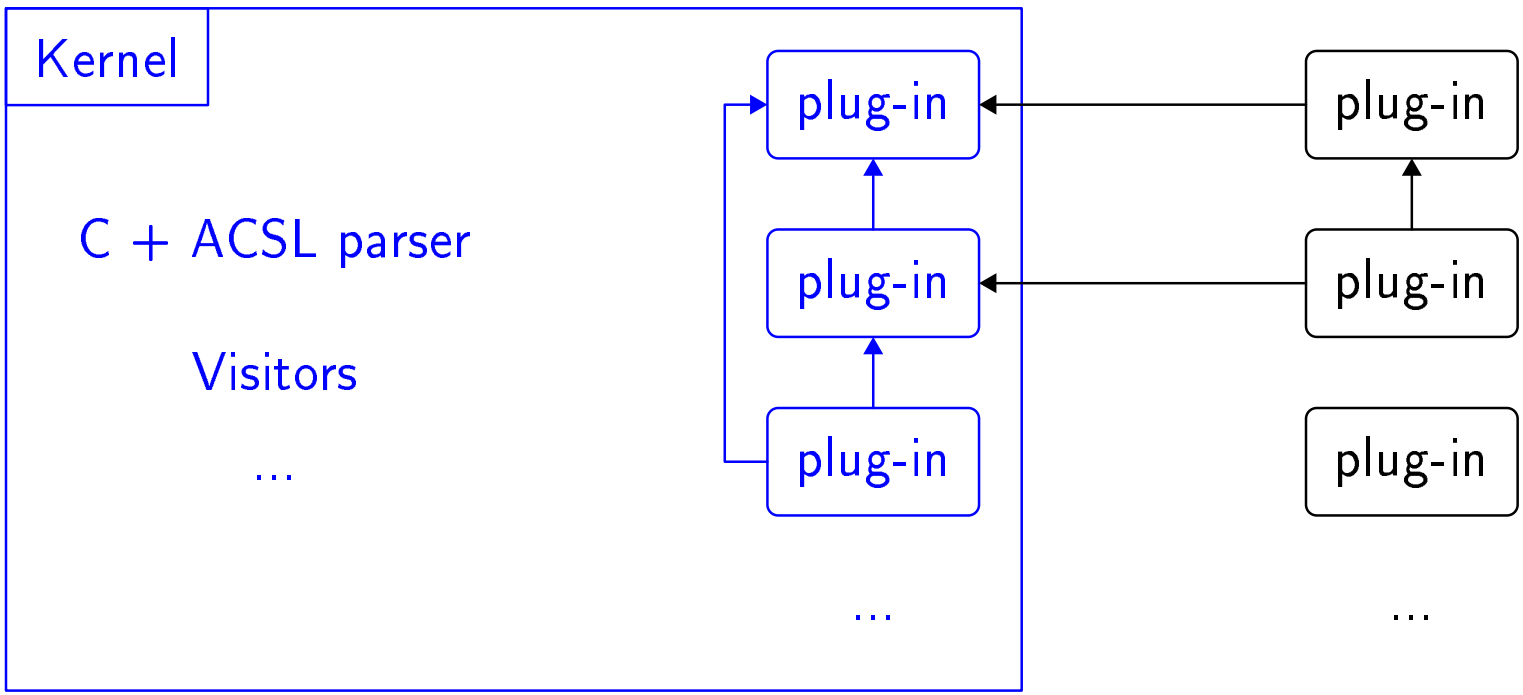
# Frama-C

CEA - LSL
Tool for collaborative and modular analyzers for C



# Jessie plug-in

## ACSL

Specification language for C programs

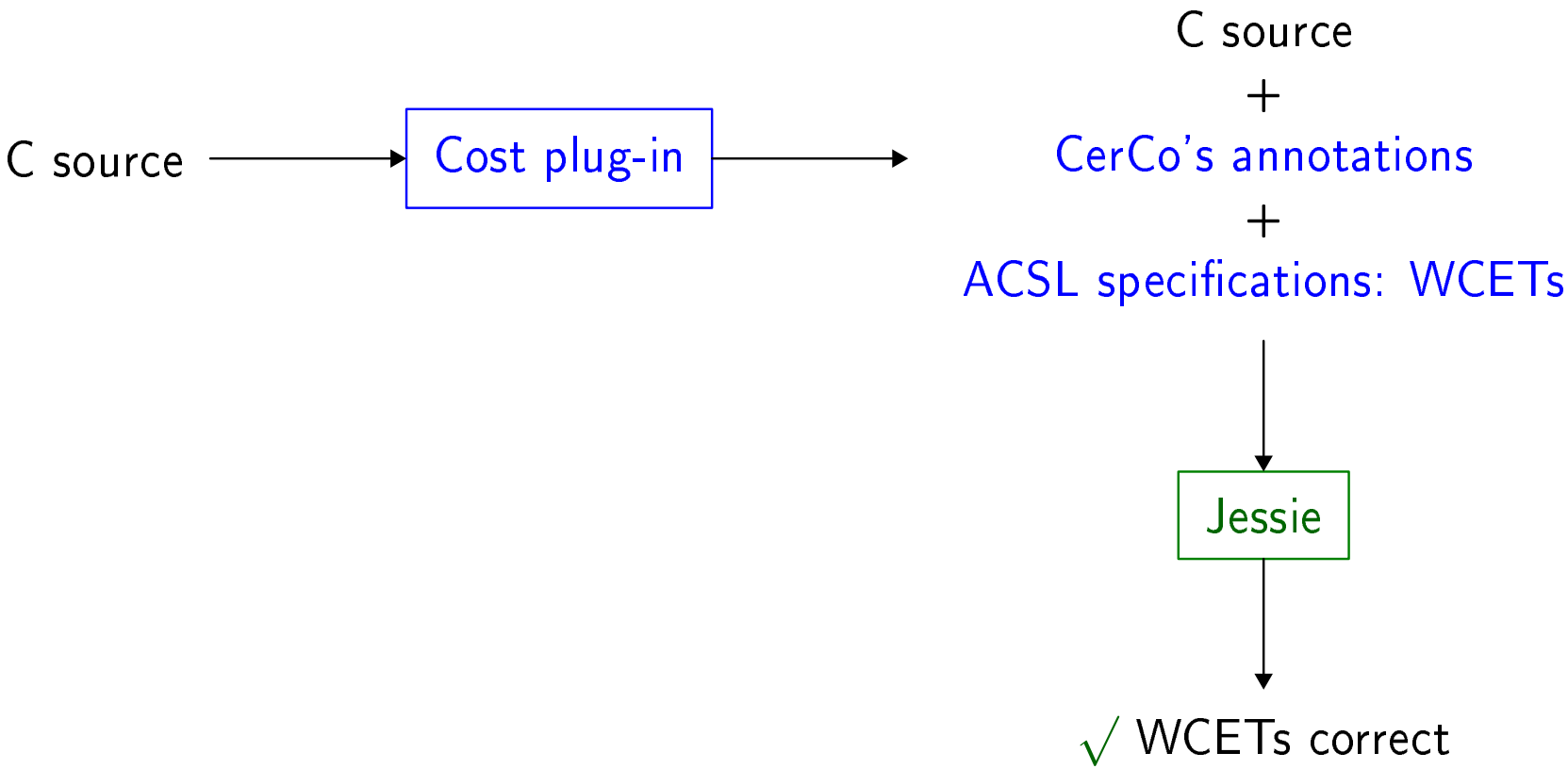
- Based on Hoare logic
- C Comments
- First-order logical definitions and propositions

## Jessie

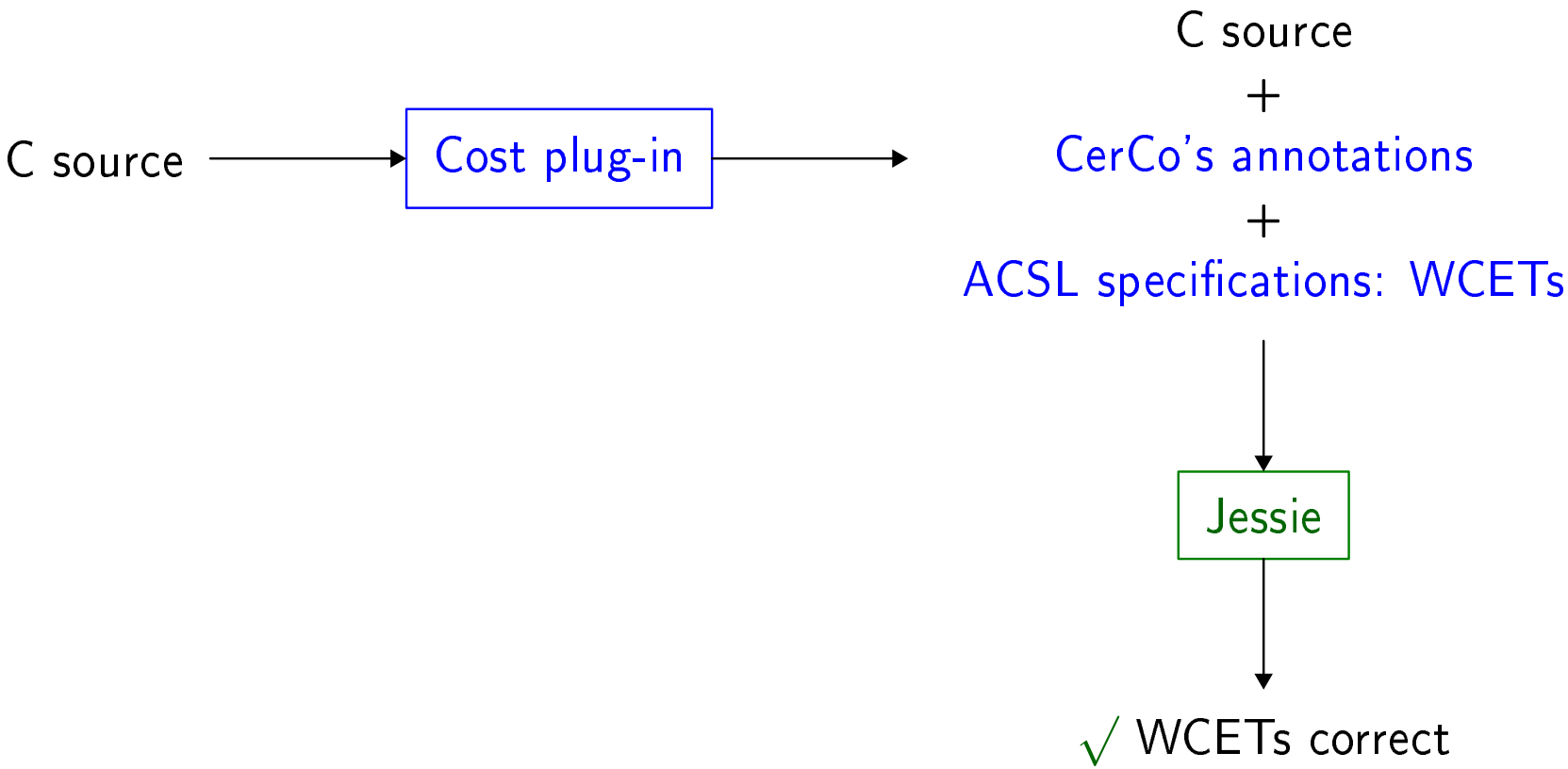
Translator to Why (LRI - ProVal)

- Weakest pre-condition calculus
- Generates proof obligations
- Output to various provers (automatic or interactive)

# Cost plug-in


C source
Cost plug-in
C source
+
CerCo's annotations
+
ACSL specifications: WCETs
Jessie
√ WCETs correct

# Cost plug-in




Demo

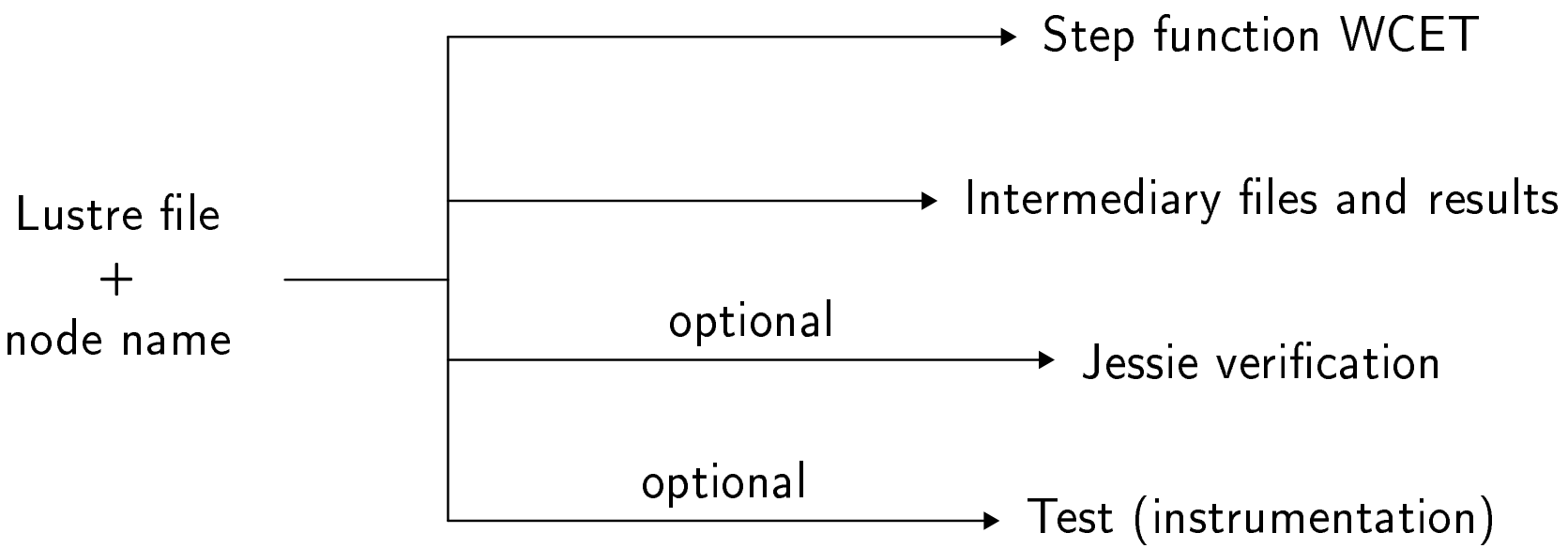
## Lustre

- Synchronous language
- Node = flow
- `lus2c`: node $\rightarrow$ C step function (cycle)
- Step function WCET = component reaction time

### Lustre C specificities

- No arrays
- No loop
- Boolean variables identified

# Wrapper for Lustre



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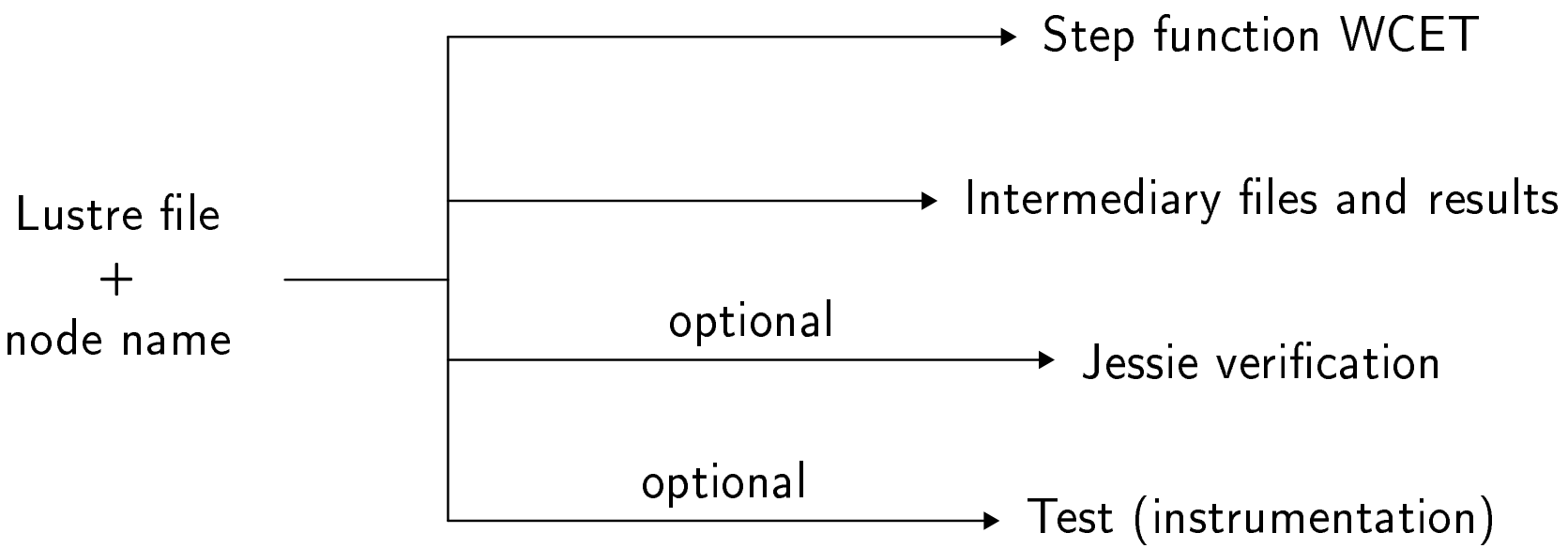


Demo

# Conclusion

## CerCo

- C sound compiler (proofs in progress in Matita)
- Correct cost annotations (overapproximation)
- C analyzers for WCET
- Symbolic cost labels
- Modular proofs

Thank you for your attention!

Questions?