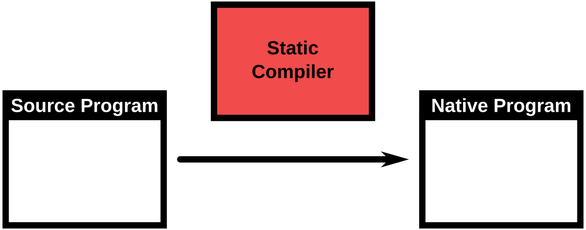
Verified native code generation in a JIT compiler

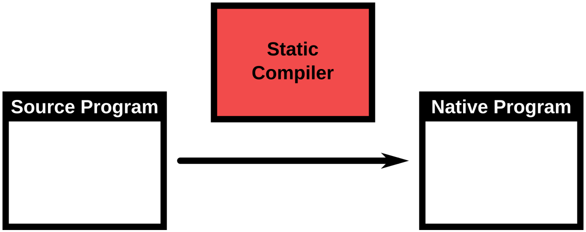
Cambium Seminar

Aurèle Barrière Sandrine Blazy David Pichardie

May 30th, 2022

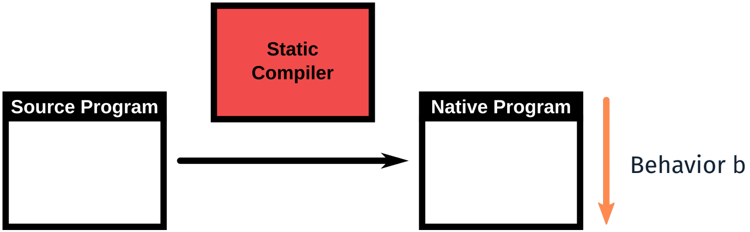
Formally verified **static** compilation





State of the Art: Verified static compilers

CompCert [Leroy 2006], CakeML [Kumar et al. 2014], VeLLVM [Zhao et al. 2012].
Compilation happens **statically**: the code is produced before its execution.



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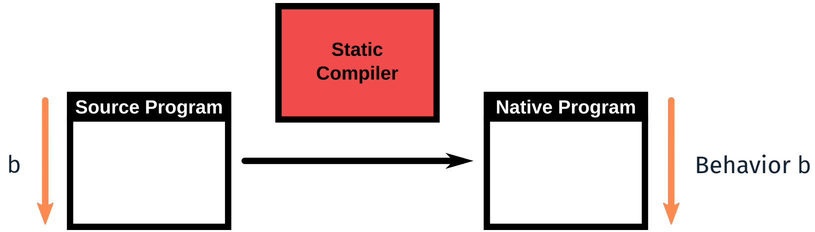

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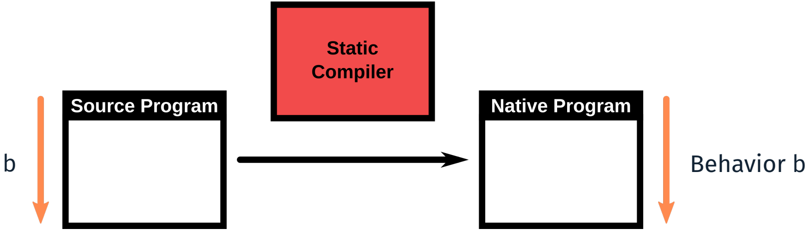

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What about JIT compilation verification?

JIT compilation: Interleave execution and optimization of the program.

Execution Stack

Interpreter: f

Program

```
Function f():
 while (...):
  g()

Function g():
 g1
 g2
```

Execution Stack

Interpreter: `f`

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Executing a program with a JIT with speculative optimizations

Execution Stack

Interpreter: `f`

Optimizing Compiler

Program

```
Function f():
 while (...):
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Function g():
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Function g_x86():
 g1
 Speculation (x=7)
 g2'
```

Execution Stack

Interpreter: `f`

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Speculation fails

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On-stack replacement

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Deoptimization requires the JIT to

- Synthesize interpreter stackframes in the middle of a function.
- Possibly synthesize many stackframes at once.

With speculation, JITs need precise execution stack manipulation.

Our Goals

A **verified** and **executable** JIT in Coq.

Modern and efficient JIT compilers features:

- Dynamic Optimizations.
- With native code generation and execution.
- With speculation and on-stack replacement.

Proof modularity and reusability:

- Using CompCert as a backend compiler (translating *RTL* to *x86*).
- Reusing CompCert's backend proof.
- Reusing CompCert's proof methodology (simulation framework).

CompCert Theorem

If we compile a program whose behaviors are free of errors, then any behavior of the compiled program is a behavior of the source program.

```
Theorem transf_c_program_is_refinement:
  ∀ p tp,
  transf_c_program p = OK tp →
  (∀ beh, program_behaves (Csem.semantics p) beh → not_wrong beh) →
  (∀ beh, program_behaves (Asm.semantics tp) beh → program_behaves (Csem.semantics p) beh).
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```

JIT Theorem

If the semantics (`CoreIR_sem`) of the program is free of errors, then any behavior of the JIT on that program (`jit_sem`) is a behavior of the program.

```
Theorem jit_same_safe_behavior:
  ∀ (p:program),
    (∀ beh, program_behaves (CoreIR_sem p) beh → not_wrong beh) →
    (∀ beh, program_behaves (jit_sem p) beh →
                              program_behaves (CoreIR_sem p) beh).
```

How do we define `jit_sem` ?

JIT-specific verification problems

- Speculative optimizations.
- Dynamic Optimizations interleaved with execution.
- Impure and non-terminating components.
- Integrate the correctness proof of a static compiler backend.

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Previous Work: Formally verified speculation and deoptimization in a JIT compiler, POPL21

Aurèle Barrière, Sandrine Blazy, Olivier Flückiger, David Pichardie, Jan Vitek.
`https://github.com/Aurele-Barriere/CoreJIT`

- CoreIR, inspired by RTL and speculative instructions ([Flückiger et al. 2018]).
- Correctness theorem of CoreJIT with interpretation, dynamic optimizations, and speculations.

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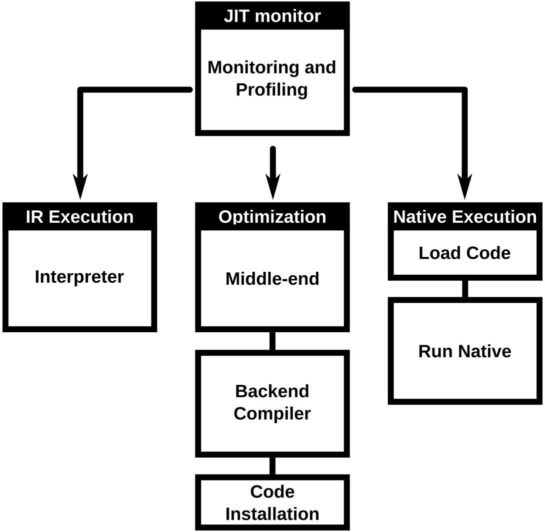
A theorem about IR to IR transformation. No native code generation in the formal model.

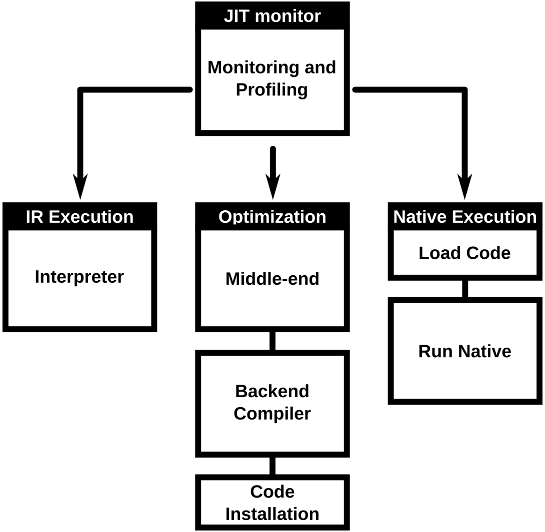


JIT architecture

Extends the architecture from [Barrière et al. 2021] with native code generation and execution.

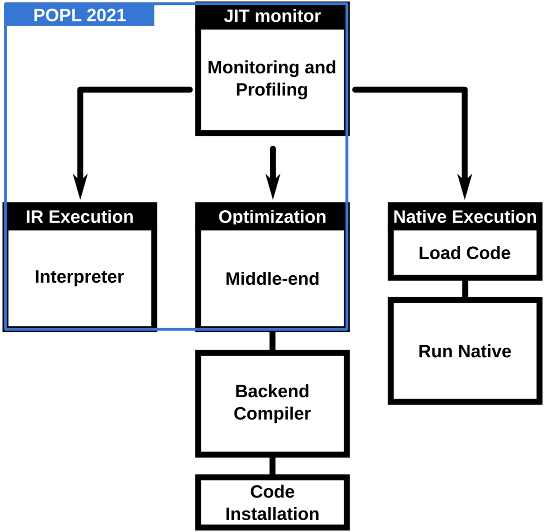
JIT loop

The **monitor** chooses the next step: execution or optimization.
Profiling: records information about the execution and suggests speculations.



Interpreter

Interpret the IR code that has not been compiled to native.



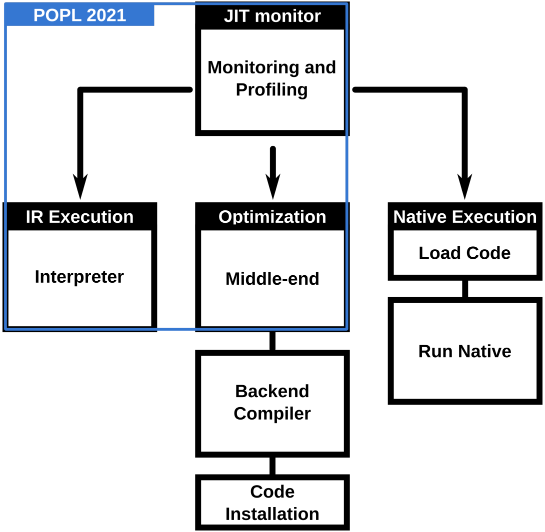
Middle-end Optimizer

From the IR to the IR.
Inserts speculation.

POPL21

The correctness theorem of our previous work is about these components.
A Coq proof that any behavior of this JIT prototype is a behavior of the input program.

A JIT Architecture

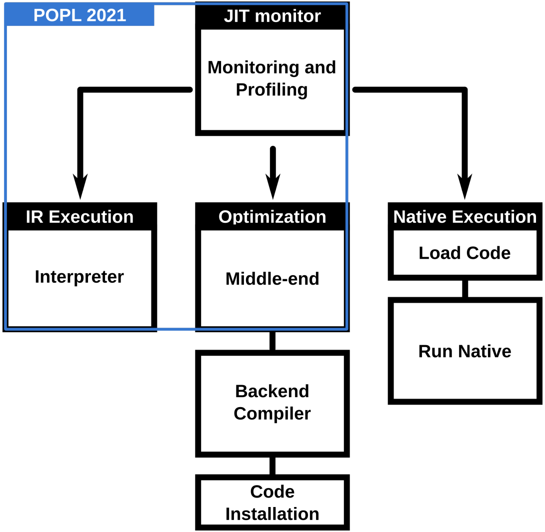


Backend Compilation

Generates native code, as in a static compiler backend.
Use the CompCert backend from RTL to x86.

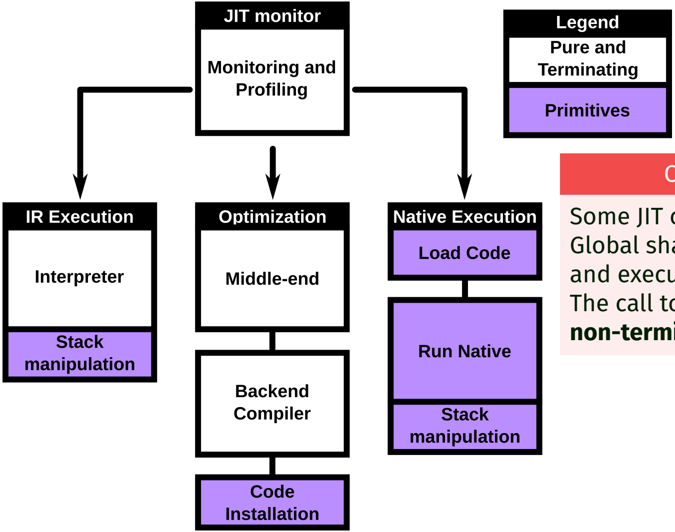
Code Installation

Install the dynamically generated code in memory.
Make it executable.



Setting up native execution
Get a function pointer for the installed code.

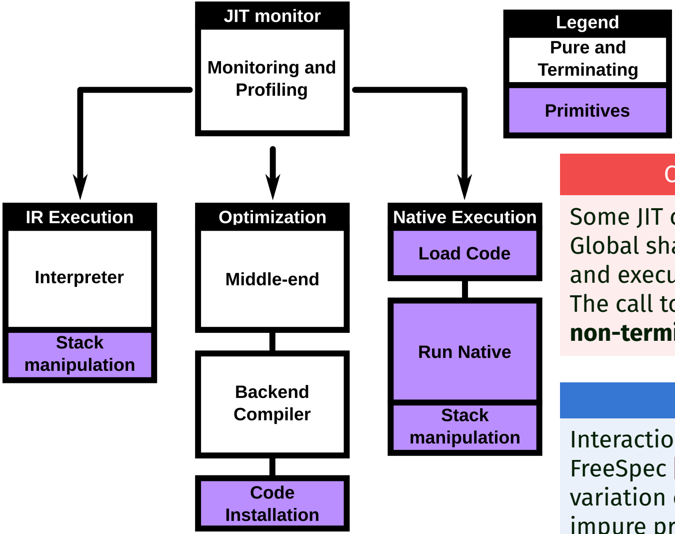
Native Code Execution
Run the generated code.



Can we really write a JIT in Coq?

Some JIT components are **impure**.
Global shared data-structures: execution stack and executable memory.
The call to native code may even be **non-terminating**.

A JIT Architecture



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Free Monads

Interaction Trees [Xia et al. 2020] and FreeSpec [Letan and Régis-Gianas 2020] use a variation of the **free monad** to reason about impure programs in Coq.

State monads are perfect to specify functions with an effect on a global state. Either the function fails, or it succeeds and returns the next global state. Found in CompCert.

```
Inductive sres (state:Type) (A:Type): Type :=
| SError : errmsg → sres state A
| SOK: A → state → sres state A.
Definition state_mon {state:Type} (A:Type) : Type := state → sres state A.
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Definition state_ret {state:Type} {A:Type} (x:A) : state_mon A :=
fun (s:state) ⇒ SOK x s.

Definition state_bind {state:Type} {A B:Type} (f: state_mon A) (g:A → state_mon B) : state_mon B :=
  fun (s:state) ⇒
    match (f s) with
    | SError msg ⇒ SError msg
    | SOK a s’ ⇒ g a s’
    end.
```

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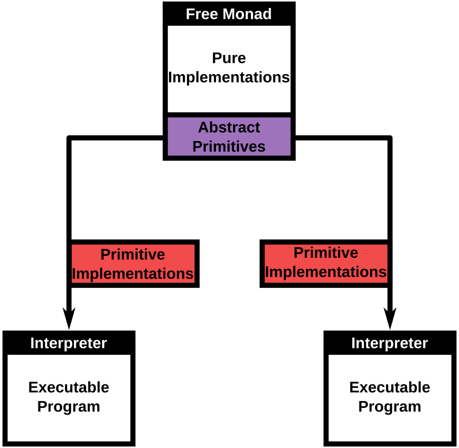
    end.
```

Executable JIT

This is fine to specify the primitives, but the actual JIT should execute actual impure primitives.

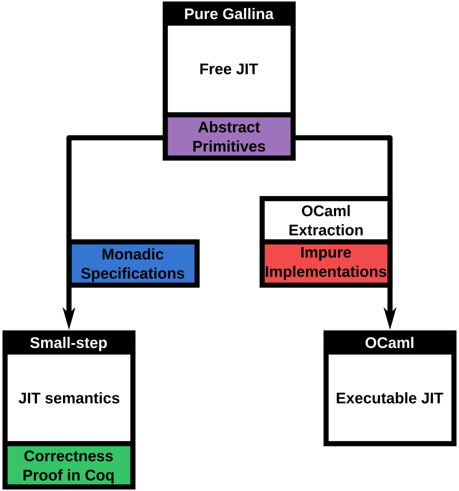
A Free Monad



Some parts of the JIT can be written in Coq, some can't. Let's find a way to write in Coq exactly the parts we want to extract to OCaml.
Free Monad: Representing programs where some impure primitives have yet to be implemented.

```
Inductive free (T : Type) : Type :=
  | pure (x : T) : free T
  | impure {R}
    (prim : primitive R) (next : R → free T): free T.
```

With different primitive implementations, the program can be executed differently.

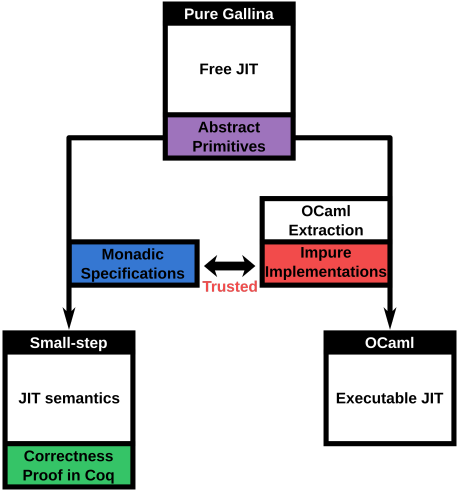


The Free JIT

A Free JIT without primitive implementations.
Given specifications, define small-step semantics.
Extract to OCaml with impure implementations.

Inspired by Free Monads, but adapted to fit the simulation framework of CompCert.

Our strategy for a verified executable impure JIT



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In that example, we want to write programs that can access a single global variable of type `nat`.

A list of primitives our programs can use:

```
Inductive primitive: Type → Type :=
| Get : primitive nat
| Put (x:nat) : primitive unit.
```

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A list of primitives our programs can use:

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We can then define Free Monads:

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Inductive free (T :Type) : Type :=
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    (prim : primitive R) (next : R → free T).
```

```
Fixpoint free_bind {X Y} (f: free X) (g: X →
free Y) : free Y :=
  match f with
   | pure x ⇒ g x
   | impure R prim next ⇒
     impure prim (fun x ⇒ free_bind (next x) g)
     end.
```

Given primitive implementations, we want to turn a free monad into an executable state monad. An **implementation** is one state monad for each primitive:

```
Record monad_impl: Type :=
  mk_mon_imp {
      prim_get: state_mon nat;
      prim_put: nat → state_mon unit; }.
```

```
Definition exec_prim {R:Type} (p:primitive R)
                (i:monad_impl) : state_mon R :=
  match p with
  | Get ⇒ prim_get i
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  end.
```

We can now give semantics to our Free Monads:

```
Fixpoint exec {A:Type} (f:free A) (i:monad_impl): state_mon A :=
  match f with
  | pure a ⇒ state_ret a
  | impure R prim cont ⇒
    state_bind (exec_prim prim i) (fun r:R ⇒ exec (cont r) i)
  end.
```

Finally, we extract the JIT free monad to OCaml.
We can write a new way to execute free monads, calling impure primitives when needed.

```
(* impure primitives *)
let nm_exec_prim (p:'x primitive) : 'x =
match p with
  | Get -> !global
  | Put (n) -> global := n

(* executing free monads *)
let rec nm_exec (f:'A free) : 'A =
  match f with
  | Coq_pure (a) -> a
  | Coq_ferror (e) -> print_error e; failwith "JIT_crashed"
  | Coq_impure (prim, cont) ->
     let x = nm_exec_prim prim in
     nm_exec (cont x)
```

Every JIT component can be written as a Free Monad:

```
Definition optimizer (f:function) : free unit :=
    do f_rtl ← ret (IRtoRTL f);
    do f_x86 ← ret (backend f_rtl); (* using CompCert backend *)
    Prim_Install_Code f_x86.
```

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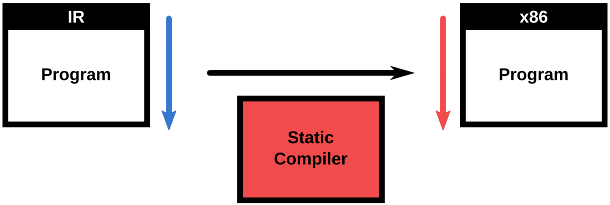
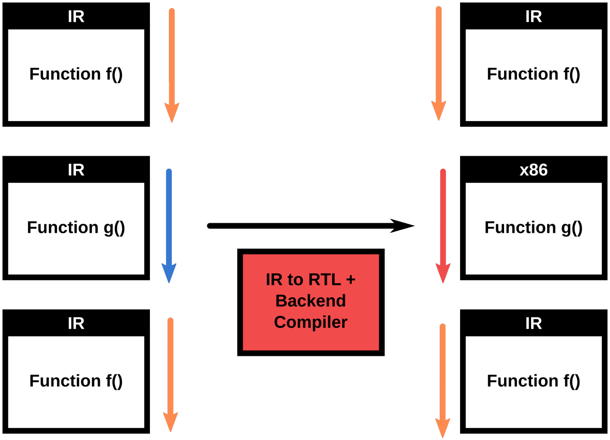
C implementation

- Calls an assembler to produce binary code.
- Allocates writable memory with `mmap`.
- Writes the binary code in that memory.
- Makes the memory executable with `mprotect`.

CompCert preserves the observable behavior of the program.





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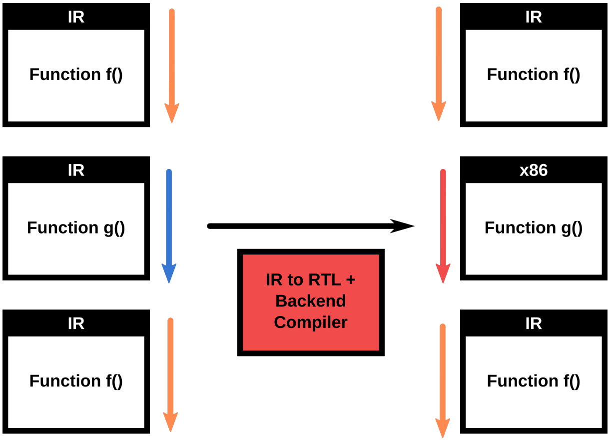

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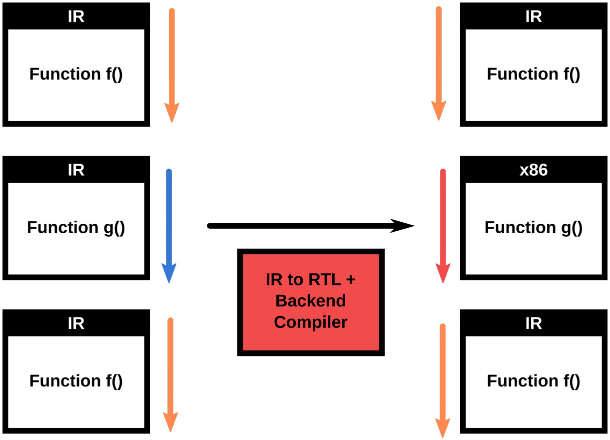
CompCert as a JIT backend

Compiles whole programs (no arguments).
Effects on the stack and heap should be preserved too.



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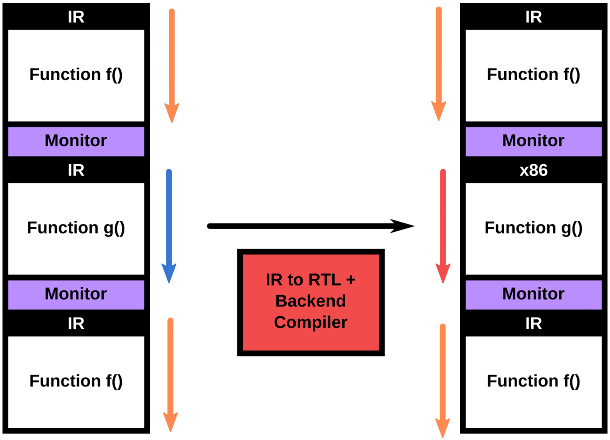

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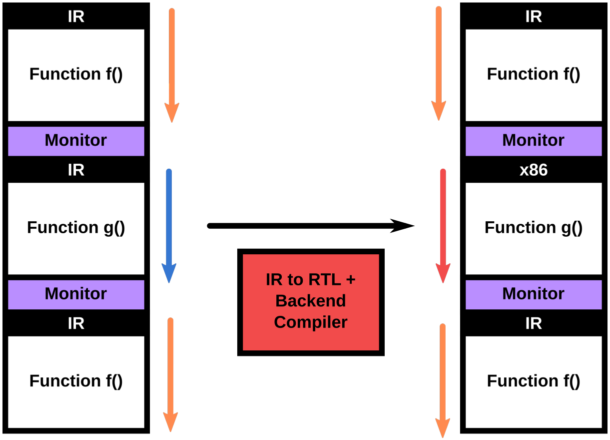
Compiling Function Calls

We have to go through the monitor.



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Compiling Function Calls

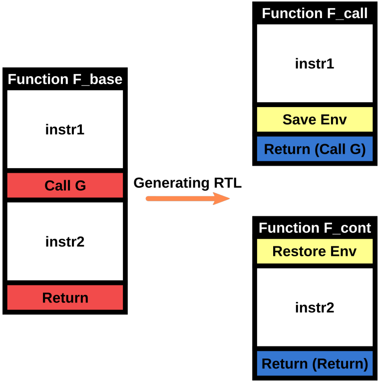
We have to go through the monitor.

Split the functions at calls.

Generating Several RTL Programs

Generating RTL code that uses custom calling conventions with our primitives.

- Primitives are *external calls*.
- Each RTL function returns to the monitor.
- One Continuation per Call instruction.



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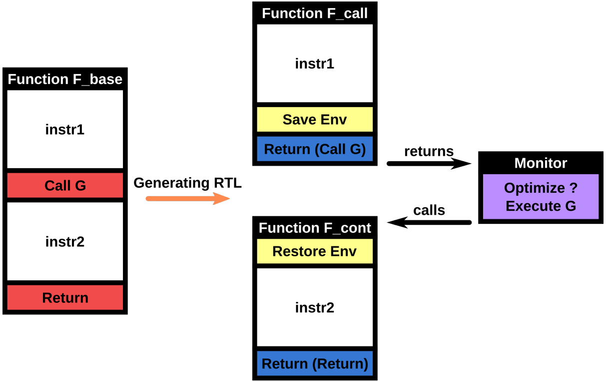

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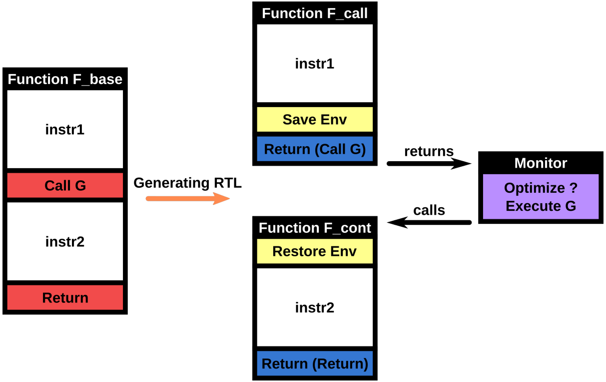
CompCert does not handle the heap and stack. It interacts with it through primitive calls.



CoreIR Function

```
Function Fun1 (reg1):
  reg2 ← Uplus 4 reg1
  reg3 ← Call Fun7 (reg2)
  reg3 ← Plus reg1 reg3
  Return reg3
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RTL Functions

```
$1() {
  x8 = "Pop"()
  x9 = x8 + 4 (int)
  x1 = "Push" (x8)
  x1 = "Close"(1, 2, 10)
  x1 = "Push"(x9)
  x1 = "Push"(1)
  x1 = "Push"(7)
  x7 = RETCALL
  return x7 }

$1() {
  x10 = "Pop"()
  x8 = "Pop"()
  x10 = x8 + x10
  x1 = "Push"(x10)
  x7 = RETRET
  return x7 }
```

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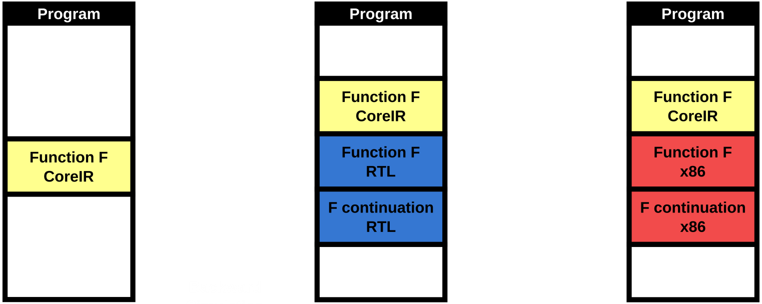
  x7 = RETRET
  return x7 }
```

Assembler Continuation Function

```
# File generated by CompCert 3.8
$1:
leaq     32(%rsp), %rax
movq     %rax, 0(%rsp)
movq     %rbx, 8(%rsp)
call     _Pop
movq     %rax, %rbx
call     _Pop
leal     0(%eax,%ebx,1), %edi
call     _Push
movl     $RETRET, %eax
movq     8(%rsp), %rbx
addq     $24, %rsp
ret
```

To get behavior equivalence, we need to prove *backward simulations* (from CompCert).



We keep the original version of F in case of deoptimizations.

From CoreIR to RTL: generate new calling conventions.

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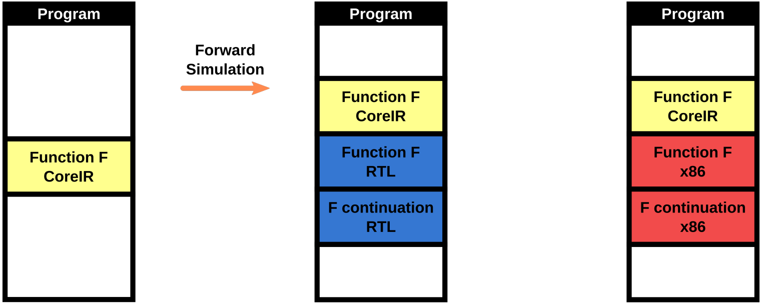

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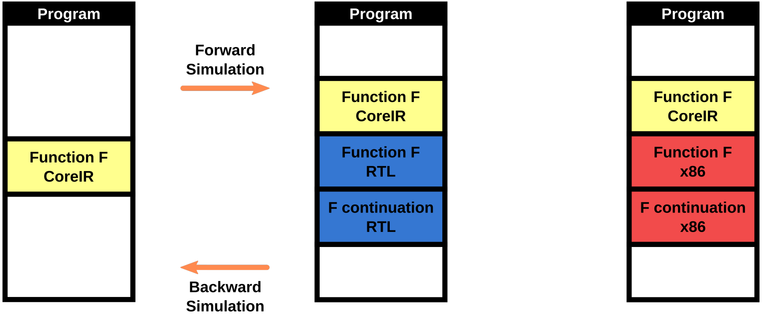

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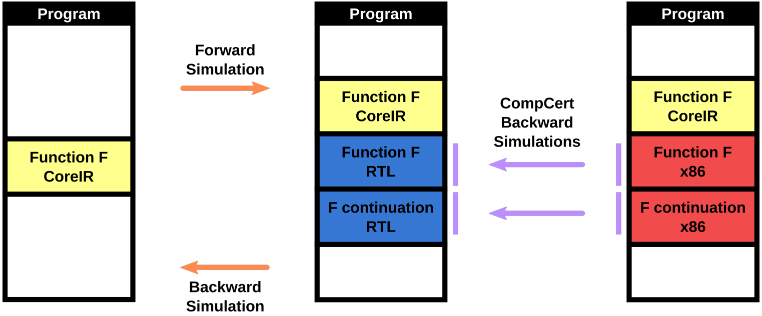
From CoreIR to RTL: generate new calling conventions.
A forward simulation is easier to prove.
And can be used to prove a backward one.

To get behavior equivalence, we need to prove *backward simulations* (from CompCert).



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From RTL to x86: use CompCert for the function and its continuations.

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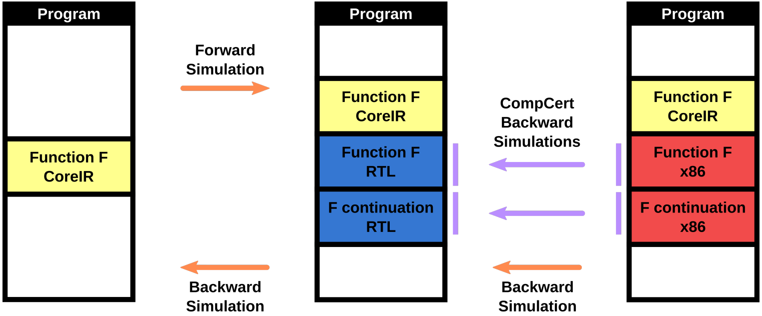
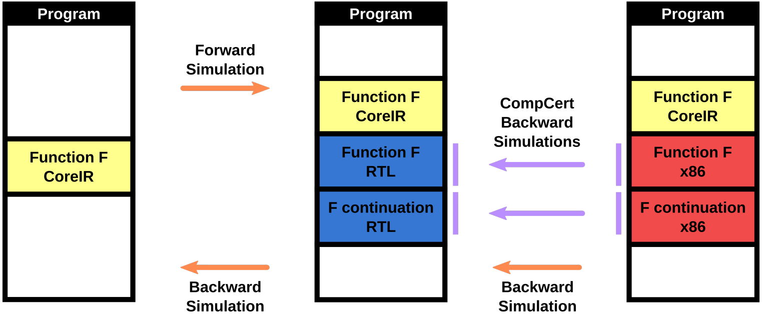


We keep the original version of F in case of deoptimizations.

From RTL to x86: use CompCert for the function and its continuations.
Use the CompCert simulations to prove a simulation for the entire program.

To get behavior equivalence, we need to prove *backward simulations* (from CompCert).



We keep the original version of F in case of deoptimizations.

```
Theorem optimizer_correct:
  ∀ p p', exec (optimizer p) = SOK p' →
    backward_simulation p p'.
```

Output, Stack and Heap Primitives

- `Print`
- `Pop` and `Push`
- `MemSet` and `MemGet`
- Push and pop entire interpreter stackframes

Code Segment Primitives

- Install a native function in the executable memory.
- Load a function (or one of its continuations).
- Check if a function has been compiled.

Running Native Code

We define a special primitive to run native code.
Its specification is a monad describing the small-step semantics of x86 code.

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Can be called from the native code.

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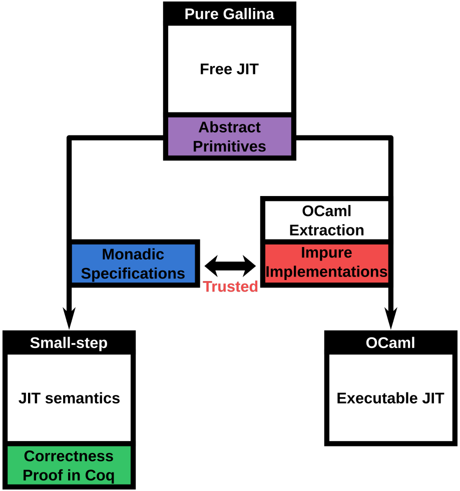
Bridging the gap between specification and implementation



What if there is a significant distance between the monadic specification and the impure implementation?

Monadic Specification (Coq)

A list of stackframe: its structure helps us write simulation invariants.

```
Record ASM_stackframe: Type := mk_sf {
  caller: int;
  next_pc: int;
  retreg: int;
  live_regs: list int }.
```

```
(* List of complete stackframes and
   the incomplete one at the top *)
Definition stack: Type :=
  list ASM_stackframe * list int.
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Impure implementation (C)

Unstructured array that the native code can access.

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int stack[STACK_SIZE];
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Definition stack: Type :=
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An intermediate Monadic Specification (Coq)

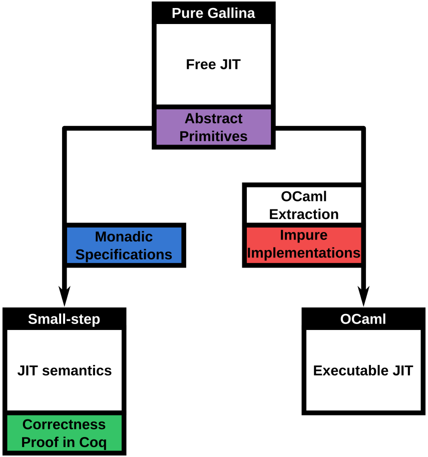
Unstructured specification, closer to the C implementation.

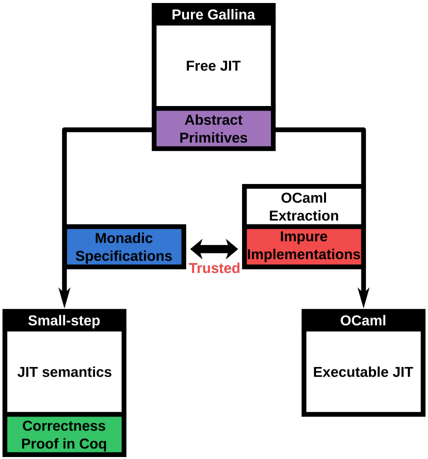
```
Definition stack: Type := list int.
```

Impure implementation (C)

Unstructured array that the native code can access.

```
int stack[STACK_SIZE];
int sp = 0;
```


Pure Gallina
Free JIT
Abstract Primitives
Monadic Specifications
OCaml Extraction
Impure Implementations
Small-step
JIT semantics
Correctness Proof in Coq
OCaml
Executable JIT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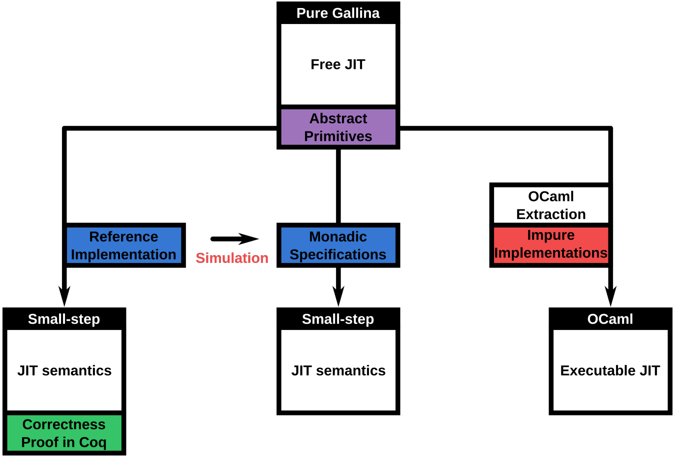
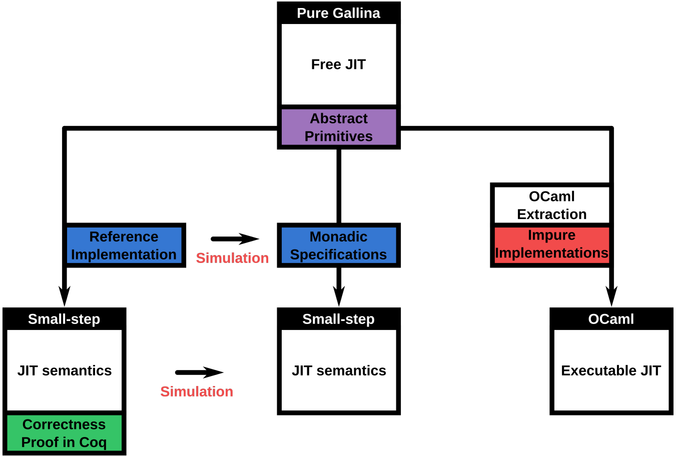
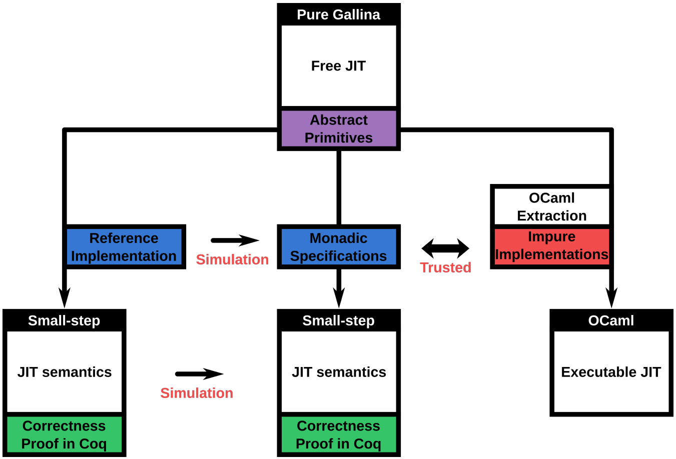
Refinement with Implementation Simulation



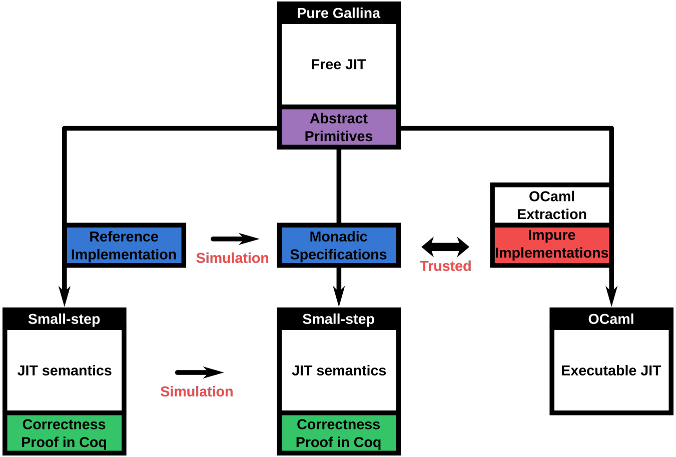
Refinement with Implementation Simulation



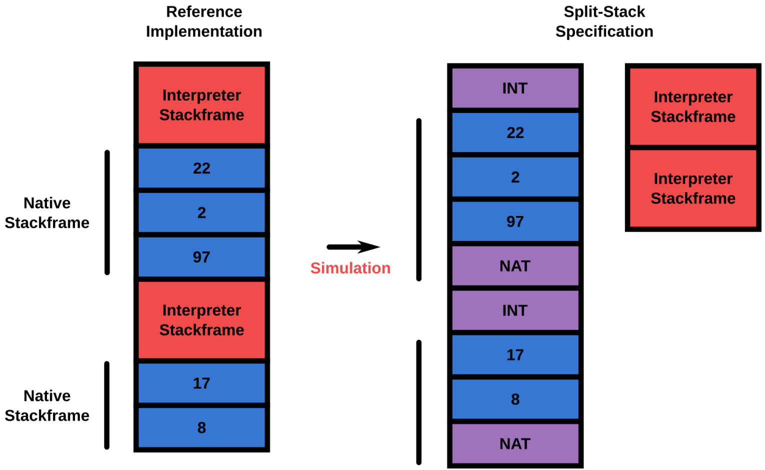
Refinement with Implementation Simulation



Refinement with Implementation Simulation




```
Theorem refines:
  ∀ prog i j
    (R: implementation_simulation i j),
    forward_simulation (monad_sem prog i) (monad_sem prog j).
```



Split Stack

Optimization proofs are easier to conduct on a single mixed stack. But stack primitives called from the native code should only interact with an array of integers.

A Free JIT

- We can derive both small-step semantics and an executable OCaml JIT **(ongoing)**.
- Native code generation and execution are part of the formal model.
- Each pure JIT component is properly specified and proved.
- Each impure component is specified with a state monad.
- A correctness proof of the JIT small-step semantics.
- We reuse the simulation methodology of CompCert.
- We reuse the simulation proof of CompCert's backend **(ongoing)**.

Trusted Code Base

- Coq extraction to OCaml.
- The primitive impure implementations correspond to their monadic specifications.
- The call to the generated native code has been specified with a free monad.

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