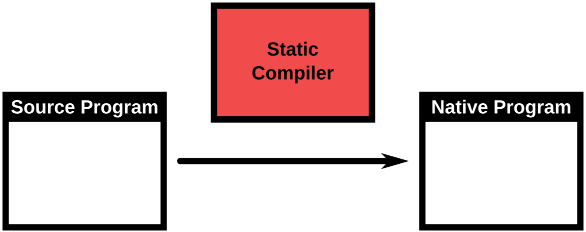
Verified native code generation in a JIT compiler

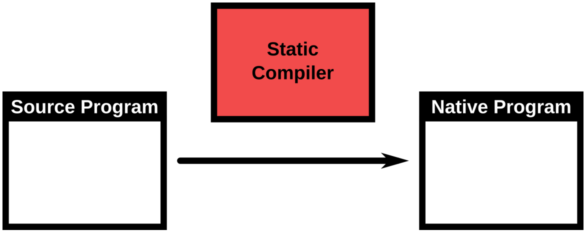
Journée hybride LVP

Aurèle Barrière   Sandrine Blazy   David Pichardie

November 23rd, 2021

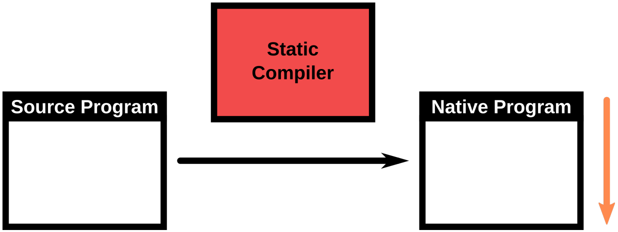
Formally verified **static** compilation





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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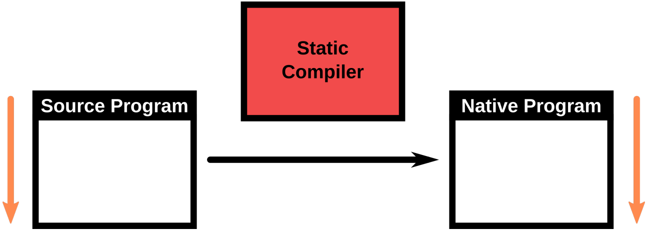

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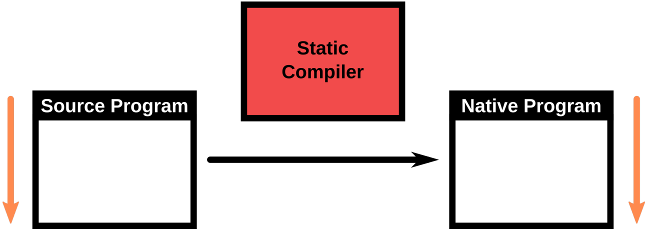

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JIT compilation

Interleave execution and optimization of the program.

Execution Stack

Interpreter: `f`

Program

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

Function g():
 g1
 g2
```

Executing a program with a JIT with speculative optimizations

Execution Stack

Interpreter: f

Interpreter: g

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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():
 g1
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Function g_x86():
 g1
 Speculation (x=7)
 g2'
```

Executing a program with a JIT with speculative optimizations

Execution Stack

Interpreter: `f`
`g_x86`

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Function f():
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Executing a program with a JIT with speculative optimizations

Execution Stack

Interpreter: `f`
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Speculation fails

Program

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Executing a program with a JIT with speculative optimizations

Execution Stack

Interpreter: `f`

~~g_x86~~

Interpreter: `g`

Speculation fails

On-stack replacement

Program

```
Function f():
 while(...):
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Function g():
 g1
 g2

Function g_x86():
 g1
 Speculation (x=7)
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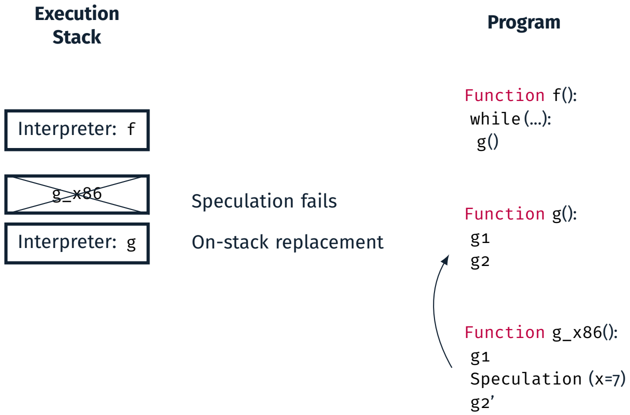
```

EXECUTING A PROGRAM WITH A JIT WITH SPECULATIVE OPTIMIZATIONS



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.
- With native code generation and execution.
- With speculation and on-stack replacement.
- Using CompCert as a backend compiler.
- Reusing CompCert's proof and its proof methodology.

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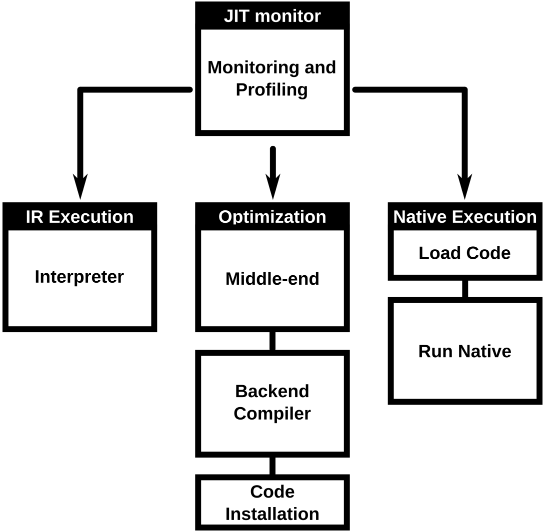
A theorem about IR to IR transformation. No native code generation in the formal model.

A JIT Architecture

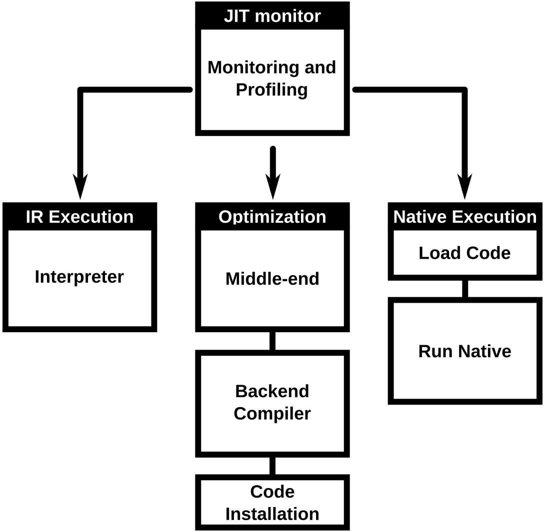


JIT architecture

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

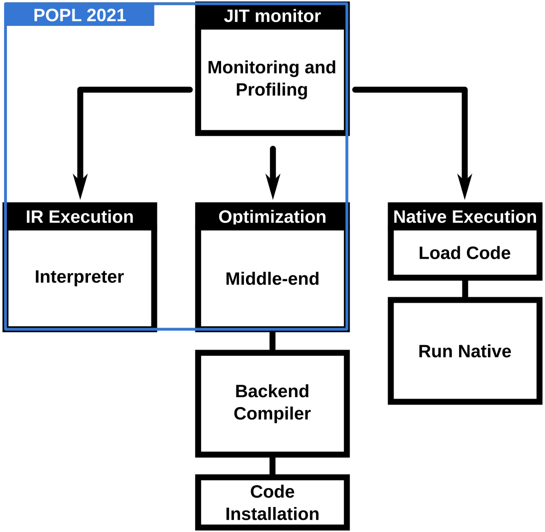
JIT loop

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



Interpreter

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

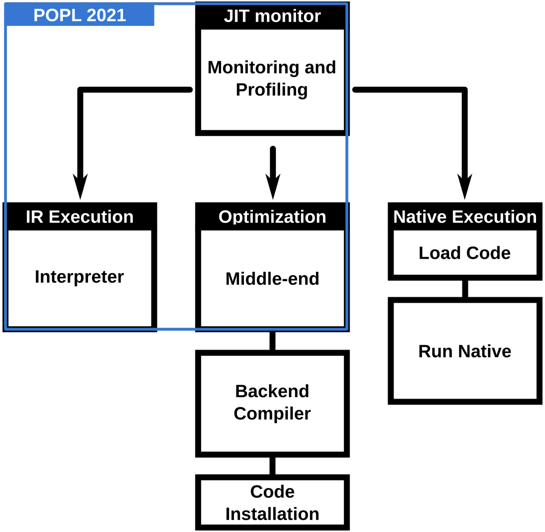


Middle-end Optimizer

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.



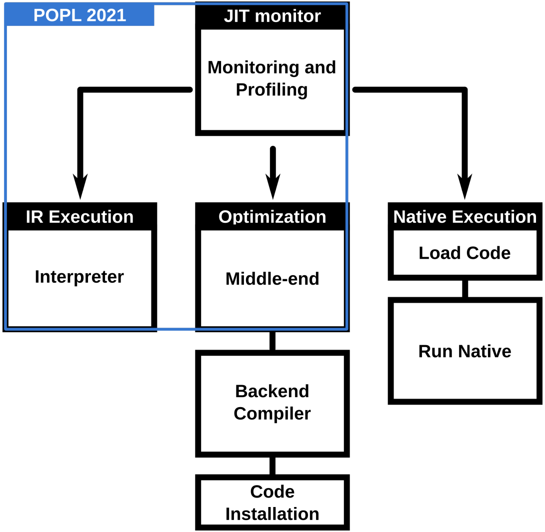
Backend Compilation

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.

A JIT Architecture



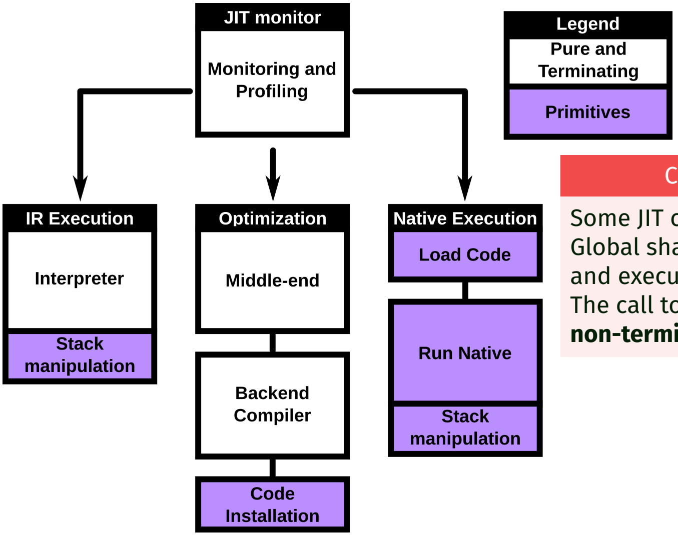
Setting up native execution

Get a function pointer for the installed code.

Native Code Execution

Run the generated code.

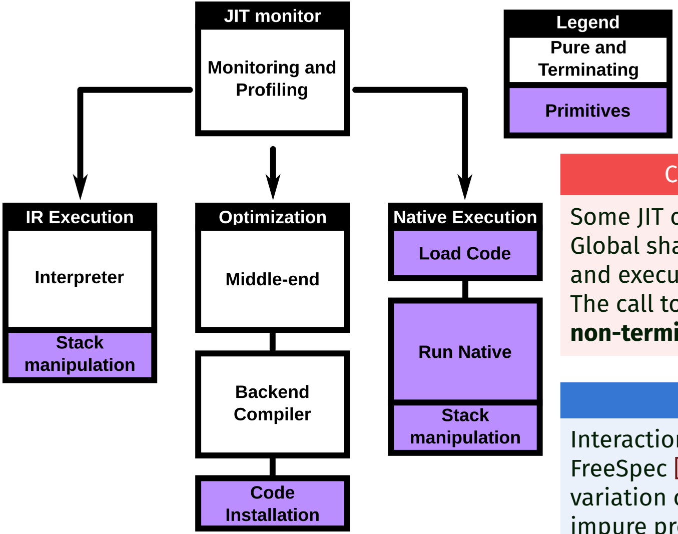
A JIT Architecture



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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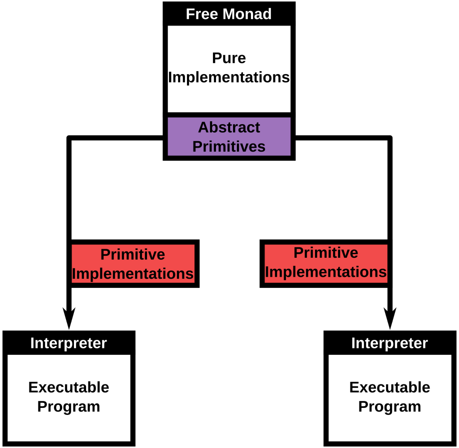
The Free Monad

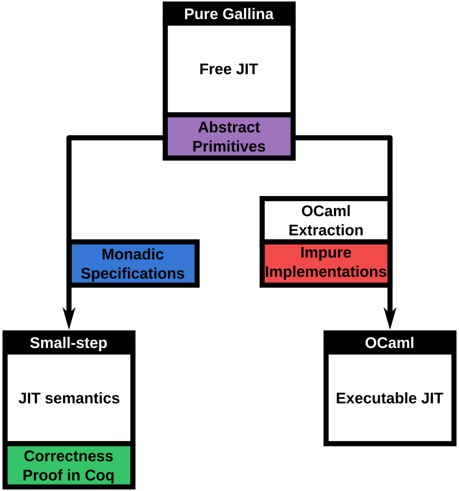
Interaction Trees [Xia et al. 2020] and FreeSpec [Letan and Régis-Gianas 2020] use a variation of the **free monad** to reason about impure programs in Coq.



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.

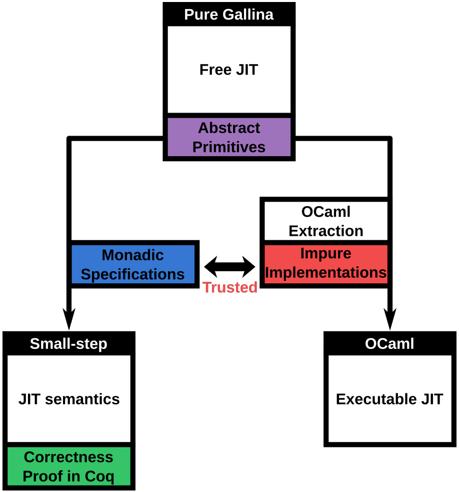


The Free JIT

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

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

Our strategy for a verified executable impure JIT



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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 *)
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New Calling Conventions

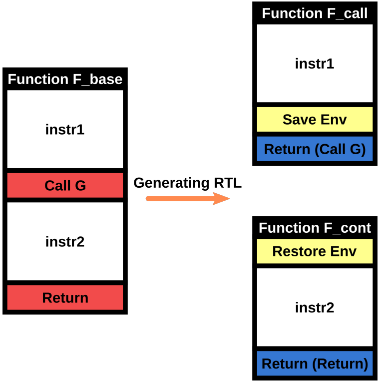
We need to reason on and manipulate the execution stack (deoptimization). Our JIT works on a custom execution stack, that only the JIT modifies.
We need to implement new calling conventions on this custom stack. The generated native code needs to call our primitives.

Generating Native Code using Primitives

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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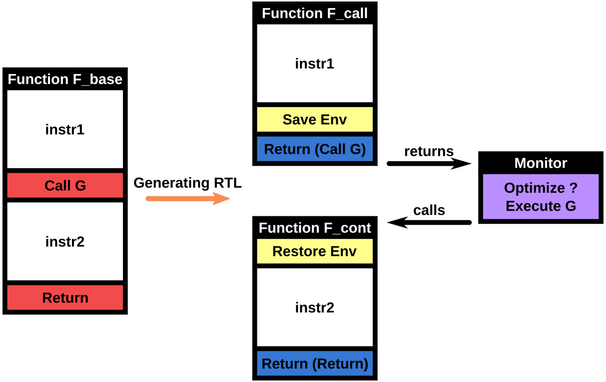

JIT Primitives

Stack Primitives

- Pop and Push
- Push and pop entire interpreter stackframes

Code Segments 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.

Conclusion

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.
- A correctness proof of the JIT small-step semantics.
- We reuse the simulation methodology of CompCert.
- We would like to 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.