VERIFIED NATIVE CODE GENERATION IN A JIT COMPILER

Cambium Seminar

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Behavior

State of the Art: Verified static compilers

CompCert [Leroy], CakeML [Kumar et al.], VeLLVM [Zhao et al.].

Compilation happens statically: the code is produced before its execution.

What about JIT compilation verification?

JIT compilation: Interleave execution and optimization of the program.
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FORMALLY VERIFIED **STATIC** COMPILATION

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What about JIT compilation verification?

JIT compilation: Interleave execution and optimization of the program.
Interpreting function $f$:

```
while(...):
  g()
```

Interpreting function $g$:

```
g1
g2
```

Speculation fails on function $g_x/eight.tosf/six.tosf$:

```
g/one.tosf
g/two.tosf
```

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.

```
two.osf
```

```
two.osf/three.osf
```
**Executing a program with a JIT with speculative optimizations**

### Execution Stack

- **Interpreter:** f
- **Interpreter:** g

### Program

**Function f():**

```python
while (...):
    g()
```

**Function g():**

```python
g1
g2
```
**Executing a program with a JIT with speculative optimizations**

**Execution Stack**

- Interpreter: f
- Optimizing Compiler

**Program**

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

- **Function g()**:  
  ```
  g1
  g2
  ```

- **Function g_x86()**:  
  ```
  g1
  Speculation (x=7)
  g2'
  ```
**Executing a program with a JIT with speculative optimizations**

**Execution Stack**

- **Interpreter:** f
- **Native:** g_x86

**Program**

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

**Function** g():
g1
g2

**Function** g_x86():
g1
Speculation (x=7)
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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.

**Program**

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

Function g():
g1
g2

Function g_x86():
g1
Speculation (x=7)
g2'
On-stack replacement

Speculation fails

Execution Stack

Interpreter: f

Native: g_x86

Interpreter: g

Program

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

Function g():
g1
g2

Function g_x86():
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Speculation (x=7)
g2'
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).
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:**

\[ \forall p \, tp, \]
\[ \text{transf}_c\text{ program} \, p = \text{OK} \, tp \rightarrow \]
\[ (\forall \, \text{beh}, \text{program\_behaves} \,(\text{Csem}\text{.semantics} \, p)\text{beh} \rightarrow \text{not\_wrong} \, \text{beh}) \rightarrow \]
\[ (\forall \, \text{beh}, \text{program\_behaves} \,(\text{Asm}\text{.semantics} \, tp)\text{beh} \rightarrow \text{program\_behaves} \,(\text{Csem}\text{.semantics} \, p)\text{beh}). \]
**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:*

\[
\forall p \; tp, \\
\text{transf_c_program} \; p = \text{OK} \; tp \rightarrow \\
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(\forall \; \text{beh}, \text{program_behaves} (\text{Asm.semantics} \; tp) \; \text{beh} \rightarrow \\
\text{program_behaves} (\text{Csem.semantics} \; p) \; \text{beh}).
\]

**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:*

\[
\forall (p: \text{program}), \\
(\forall \; \text{beh}, \text{program_behaves} (\text{CoreIR_sem} \; p) \; \text{beh} \rightarrow \text{not_wrong} \; \text{beh}) \rightarrow \\
(\forall \; \text{beh}, \text{program_behaves} (\text{jit_sem} \; p) \; \text{beh} \rightarrow \\
\text{program_behaves} (\text{CoreIR_sem} \; p) \; \text{beh}).
\]

How do we define jit_sem?
TOWARDS A FORMALLY VERIFIED JIT MIDDLE-END

<table>
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<th>JIT-specific verification problems</th>
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TOWARDS A FORMALLY VERIFIED JIT MIDDLE-END

JIT-specific verification problems

- Speculative optimizations.
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- Impure and non-terminating components.
- Integrate the correctness proof of a static compiler backend.

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.
Towards a Formally Verified JIT Middle-end

JIT-specific verification problems

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

Interpreter
Interpret the IR code that has not been compiled to native.
A JIT Architecture

POPL 2021

IR Execution
  - Interpreter

Optimization
  - Middle-end

Native Execution
  - Load Code
  - Run Native

Backend Compiler
  - Code Installation

JIT monitor
  - Monitoring and Profiling

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.
A JIT Architecture

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

Native Code Execution
Run the generated code.

**IR Execution**
- Interpreter

**Optimization**
- Middle-end

**Native Execution**
- Load Code
  - Run Native
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**.
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.

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.
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.

\[
\text{Inductive } \text{sres} \ (\text{state}:\Type) (\text{A}:\Type) : \text{Type} := \\
| \text{SError} : \text{errmsg} \rightarrow \text{sres state} \ A \\
| \text{SOK} : \text{A} \rightarrow \text{state} \rightarrow \text{sres state} \ A.
\]

\[
\text{Definition state_mon} \ {\text{state}:\Type} (\text{A}:\Type) : \text{Type} := \text{state} \rightarrow \text{sres state} \ A.
\]

\[
\text{Definition state_ret} \ {\text{state}:\Type} {\text{A}:\Type} (\text{x}:\text{A}) : \text{state_mon} \ A := \\
\text{fun} (\text{s:state}) \Rightarrow \text{SOK x s}.
\]

\[
\text{Definition state_bind} \ {\text{state}:\Type} {\text{A B}:\Type} (\text{f:state_mon} \ A) (\text{g:A} \rightarrow \text{state_mon} \ B) : \text{state_mon} \ B := \\
\text{fun} (\text{s:state}) \Rightarrow \\
\text{match} (\text{f s}) \text{with} \\
| \text{SError msg} \Rightarrow \text{SError msg} \\
| \text{SOK a s'} \Rightarrow \text{g a s'} \\
\text{end}.
\]
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.

```coq
Inductive sres (state:Type) (A:Type): Type :=
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Definition state_mon {state:Type} (A:Type): Type := state → sres state A.
```

```coq
Definition state_ret {state:Type} {A:Type} (x:A): state_mon A :=
fun (s:state) ⇒ SOK x s.
```

```coq
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.
```

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.

\[
\text{Inductive free (T : Type) : Type :=}
\begin{align*}
&\mid \text{pure (x : T)} : \text{free T} \\
&\mid \text{impure \{R\}} \\
&\quad (\text{prim : primitive R})(\text{next : R \to free T}) : \text{free T}.
\end{align*}
\]

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


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


Inspired by Free Monads, but adapted to fit the simulation framework of CompCert.
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 \rightarrow Type :=
| Get: primitive nat
| Put(x:nat): primitive unit.
Free Monad Definitions - An Example

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**: $\text{Type} \to \text{Type} :=$
- Get: primitive nat
- Put($x$: nat): primitive unit.

We can then define Free Monads:

- **Inductive free ($T$: Type): Type :=**
  - pure($x$: $T$): free $T$
  - impure {$R$}
    $(\text{prim: primitive } R)(\text{next: } R \to \text{free } T)$.

- **Fixpoint free_bind {X Y} (f: free X) (g: X \to free Y): free Y :=**
  
  match $f$ with
  - pure $x$ $\Rightarrow$ $g$ $x$
  - impure $R$ prim next $\Rightarrow$
    impure prim ($\text{fun } x \Rightarrow \text{free_bind (next } x \text{)} g$)
  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:

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

```hs
Definition exec_prim{R:Type}(p:primitive R) (i:monad_impl): state_mon R :=
match p with
| Get ⇒ prim_get i
| Put x ⇒ prim_put i x
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:

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mk_mon_impl {  
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```

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.
```

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

**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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CompCert as a JIT backend

Compiles whole programs (no arguments). Effects on the stack and heap should be preserved too.
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Make the generated code call the primitives. The stack and heap are external, not part of the CompCert memory model.
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Compiling Function Calls

We have to go through the monitor.
CompCert preserves the observable behavior of the program.

**CompCert as a JIT backend**

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

Make the generated code call the primitives. The stack and heap are external, not part of the CompCert memory model.

**Compiling Function Calls**

We have to go through the monitor.

Split the functions at calls.
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.
Generating RTL code that uses custom calling conventions with our primitives.

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Generating 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.

CompCert does not handle the heap and stack. It interacts with it through primitive calls.
**Generating Natice Code using Primitives - An Example**

CoreIR Function

```plaintext
Function Fun1 (reg1):
    reg2 ← Uplus 4 reg1
    reg3 ← Call Fun7 (reg2)
    reg3 ← Plus reg1 reg3
Return reg3
```
**Generating Native Code Using Primitives - An Example**

**CoreIR Function**

Function Fun1 (reg1):
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reg3 ← Call Fun7 (reg2)
reg3 ← Plus reg1 reg3
Return reg3

**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 }
```
### Generating Native Code using Primitives - An Example

<table>
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<th>CoreIR Function</th>
<th>RTL Functions</th>
<th>Assembler Continuation Function</th>
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<tbody>
<tr>
<td>Function Fun1 (reg1):</td>
<td>$1()$ {</td>
<td># File generated by CompCert 3.8</td>
</tr>
<tr>
<td>reg2 ← Uplus 4 reg1</td>
<td>x8 = &quot;Pop&quot;()</td>
<td>$1:$</td>
</tr>
<tr>
<td>reg3 ← Call Fun7 (reg2)</td>
<td>x9 = x8 + 4 (int)</td>
<td>leaq 32(%rsp), %rax</td>
</tr>
<tr>
<td>reg3 ← Plus reg1 reg3</td>
<td>x1 = &quot;Push&quot; (x8)</td>
<td>movq %rax, 0(%rsp)</td>
</tr>
<tr>
<td>Return reg3</td>
<td>x1 = &quot;Close&quot;(1, 2, 10)</td>
<td>movq %rbx, 8(%rsp)</td>
</tr>
<tr>
<td>$1()$ {</td>
<td>x1 = &quot;Push&quot;(x9)</td>
<td>call _Pop</td>
</tr>
<tr>
<td></td>
<td>x1 = &quot;Push&quot;(1)</td>
<td>movq %rax, %rbx</td>
</tr>
<tr>
<td></td>
<td>x1 = &quot;Push&quot;(7)</td>
<td>call _Pop</td>
</tr>
<tr>
<td></td>
<td>x7 = RETCALL</td>
<td>leal o(%eax,%ebx,1), %edi</td>
</tr>
<tr>
<td></td>
<td>}</td>
<td>call _Push</td>
</tr>
<tr>
<td></td>
<td></td>
<td>movl $RETRET, %eax</td>
</tr>
<tr>
<td></td>
<td></td>
<td>movq 8(%rsp), %rbx</td>
</tr>
<tr>
<td></td>
<td></td>
<td>addq $24, %rsp</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ret</td>
</tr>
</tbody>
</table>
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.
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. A forward simulation is easier to prove.
To get behavior equivalence, we need to prove *backward simulations* (from CompCert).

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

We keep the original version of F in case of deoptimizations.
To get behavior equivalence, we need to prove *backward simulations* (from CompCert).

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

We keep the original version of F in case of deoptimizations.
To get behavior equivalence, we need to prove *backward simulations* (from CompCert).

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

We keep the original version of F in case of deoptimizations.
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:**
\[ \forall p, p', \text{exec (optimizer p)} = \text{SOK p'} \rightarrow \text{backward_simulation p p'} \]
JIT PRIMITIVES

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.
Output, Stack and Heap Primitives

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

Can be called from the native code.

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.
What if there is a significant distance between the monadic specification and the impure implementation?
A list of stackframe: its structure helps us write simulation invariants.

```coq
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.
```
Monadic Specification (Coq)

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

Impure implementation (C)

Unstructured array that the native code can access.

```c
int stack[STACK_SIZE];
int sp = 0;
```
Monadic Specification (Coq)

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

Record ASM_stackframe: Type := mk_sf{
    caller: int;
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(* List of complete stackframes and the incomplete one at the top *)

Definition stack: Type := list ASM_stackframe * list int.

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;
Refinement with Implementation Simulation

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

Trusted
Refinement with Implementation Simulation

Pure Gallina
  - Free JIT

Abstract Primitives

Reference Implementation
  - Simulation

Monadic Specifications

OCaml Extraction
  - Impure Implementations

Small-step
  - JIT semantics
  - Correctness Proof in Coq

Small-step
  - JIT semantics

OCaml
  - Executable JIT

Simulation
Theorem refines:
\[ \forall \text{prog}_i \text{j} \]
\[(R:\text{implementation_simulation}_i\text{j}), \text{forward_simulation} (\text{monad}_\text{sem}_\text{prog}_i)(\text{monad}_\text{sem}_\text{prog}_\text{j})].\]
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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