Specialist Meeting at Imperial College, April 2016

A New Verified Compiler Backend for

CakeML

Main contributors to date: Anthony Fox, Ramana Kumar, Magnus Myreen, Michael Norrish, Scott Owens, Yong Kiam Tan

CHALMERS UNIVERSITY OF TECHNOLOGY · UNIVERSITY OF CAMBRIDGE · NICTA · DATA 61 CSIRO · University of Kent

CakeML

What?

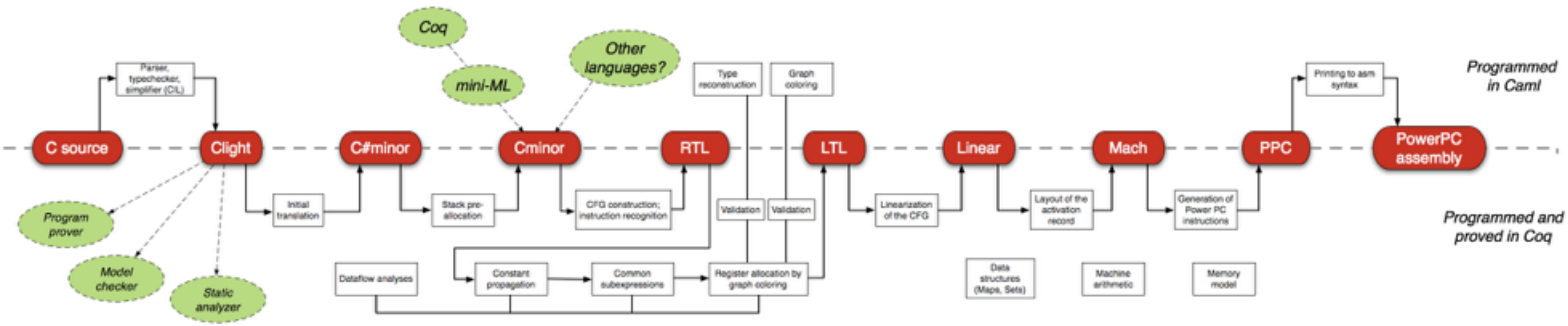
strict evaluation, stateful

1. A *programming language* in the style of Standard ML and OCaml.
2. An *ecosystem* of proofs and verification tools
3. A *verified, end-to-end development*

Verified compilation…

State of the art

CompCert



Leroy et al. ***Source:*** http://compcert.inria.fr/

Compiles C source code to assembly

Good performance numbers

Ecosystem: ***Verified Software Toolchain - Princeton University***

Verified compilation…

…for functional languages?

Answer:* *Many, but all are 'toy'.

Attempt: CakeML first 'realistic' verified ML compiler (plus ecosystem).

The CakeML language

CakeML, the language
≈ Standard ML without functors

i.e. with almost everything else:

- ✓ higher-order functions
- ✓ mutual recursion and polymorphism
- ✓ datatypes and (nested) pattern matching
- ✓ references and (user-defined) exceptions
- ✓ arbitrary-precision integers
- ✓ modules, signatures, abstract types

Update! New since POPL'14:

- ✓ foreign-function interface
- ✓ mutable arrays, byte arrays, bytes
- ✓ vectors strings, chars
- ✓ type abbreviations

e

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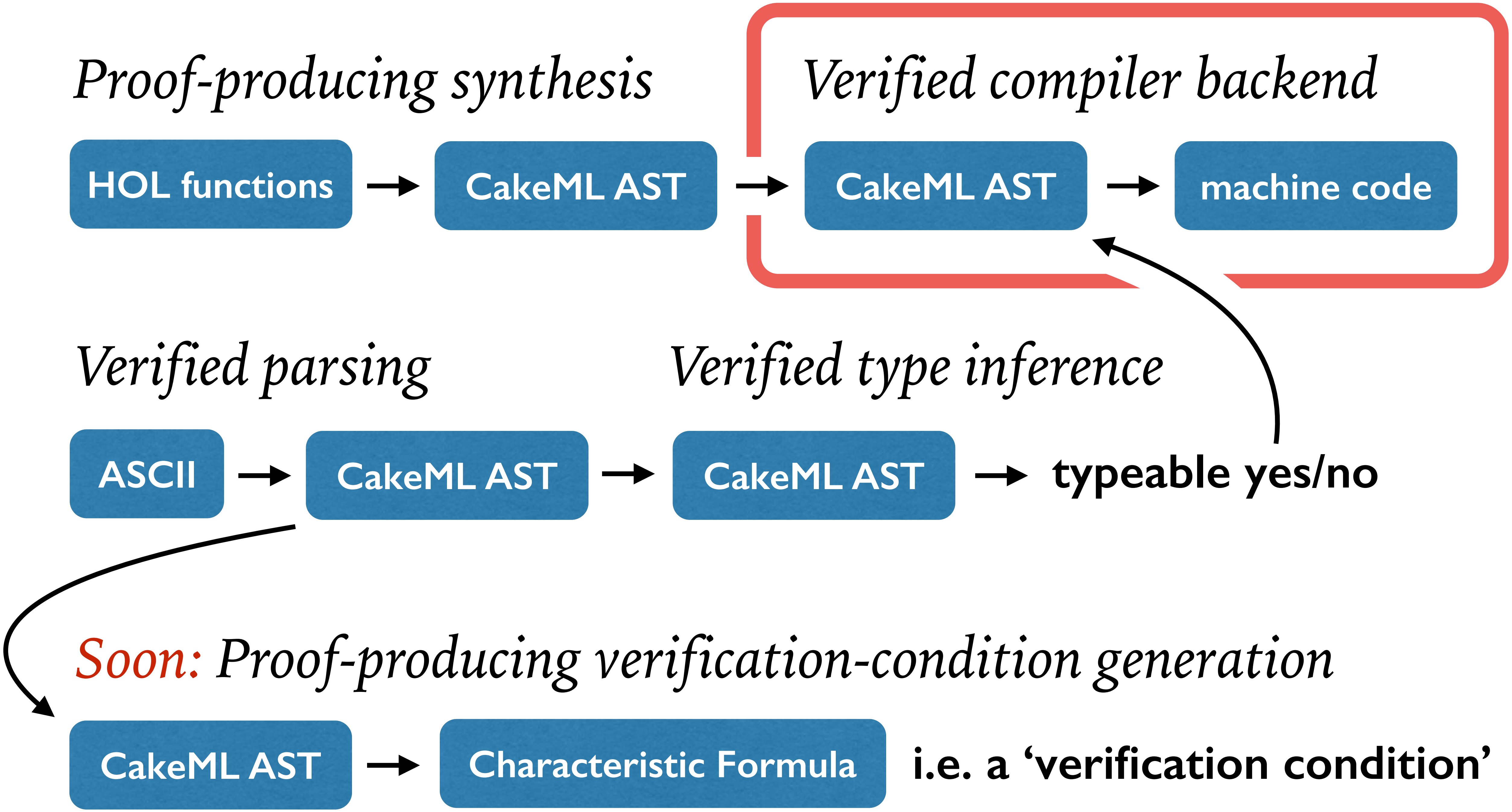
Ecosystem



Also: x86 implementation with read-eval-print-loop

This talk: **Compiler verification**

user expectations

gap

observational behaviour of source code

proved connection

modelled behaviour of generated machine code

gap

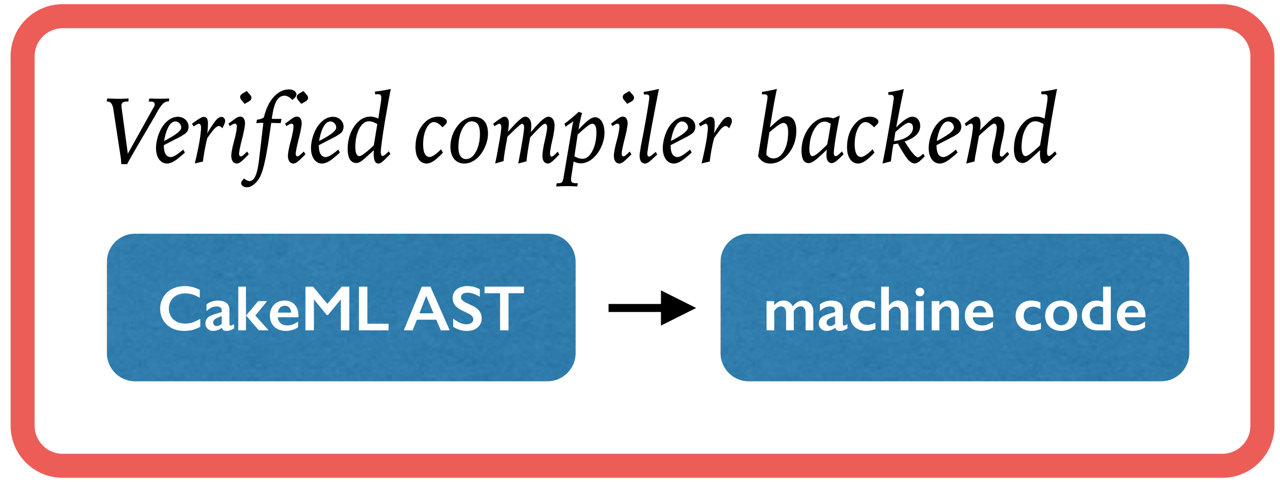
real behaviour of hardware

Verified compiler backend

CakeML AST → machine code

The entire development is in the HOL4 theorem prover.

The CakeML compiler

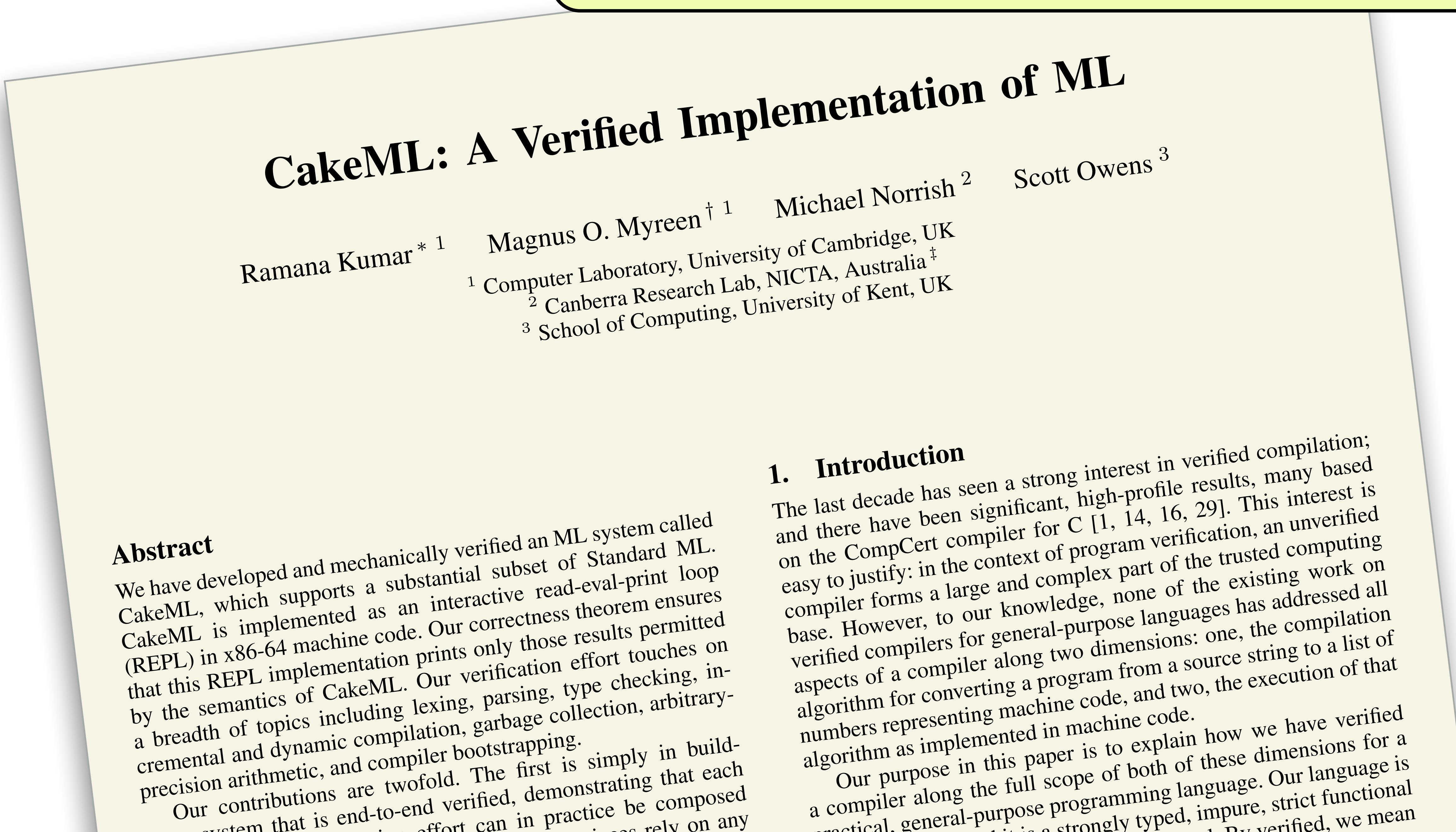


Version 1 & 2

Version 1

POPL'14

First bootstrapping of a verified compiler.



CakeML: A Verified Implementation of ML

Ramana Kumar [* 1] Magnus O. Myreen [† 1] Michael Norrish [2] Scott Owens [3]

[1] Computer Laboratory, University of Cambridge, UK
[2] Canberra Research Lab, NICTA, Australia [‡]
[3] School of Computing, University of Kent, UK

Abstract

We have developed and mechanically verified an ML system called CakeML, which supports a substantial subset of Standard ML. CakeML is implemented as an interactive read-eval-print loop (REPL) in x86-64 machine code. Our correctness theorem ensures that this REPL implementation prints only those results permitted by the semantics of CakeML. Our verification effort touches on a breadth of topics including lexing, parsing, type checking, incremental and dynamic compilation, garbage collection, arbitrary-precision arithmetic, and compiler bootstrapping.

Our contributions are twofold. The first is simply in build-

1. Introduction

The last decade has seen a strong interest in verified compilation; and there have been significant, high-profile results, many based on the CompCert compiler for C [1, 14, 16, 29]. This interest is easy to justify: in the context of program verification, an unverified compiler forms a large and complex part of the trusted computing base. However, to our knowledge, none of the existing work on verified compilers for general-purpose languages has addressed all aspects of a compiler along two dimensions: one, the compilation algorithm for converting a program from a source string to a list of numbers representing machine code, and two, the execution of that algorithm as implemented in machine code.

Our purpose in this paper is to explain how we have verified a compiler along the full scope of both of these dimensions for a

Dimensions of Compiler Verification

source code

abstract syntax

intermediate language

VM bytecode

machine code

how far compiler goes

First verification to cover the full spectrum of **both** dimensions.

compiler algorithm

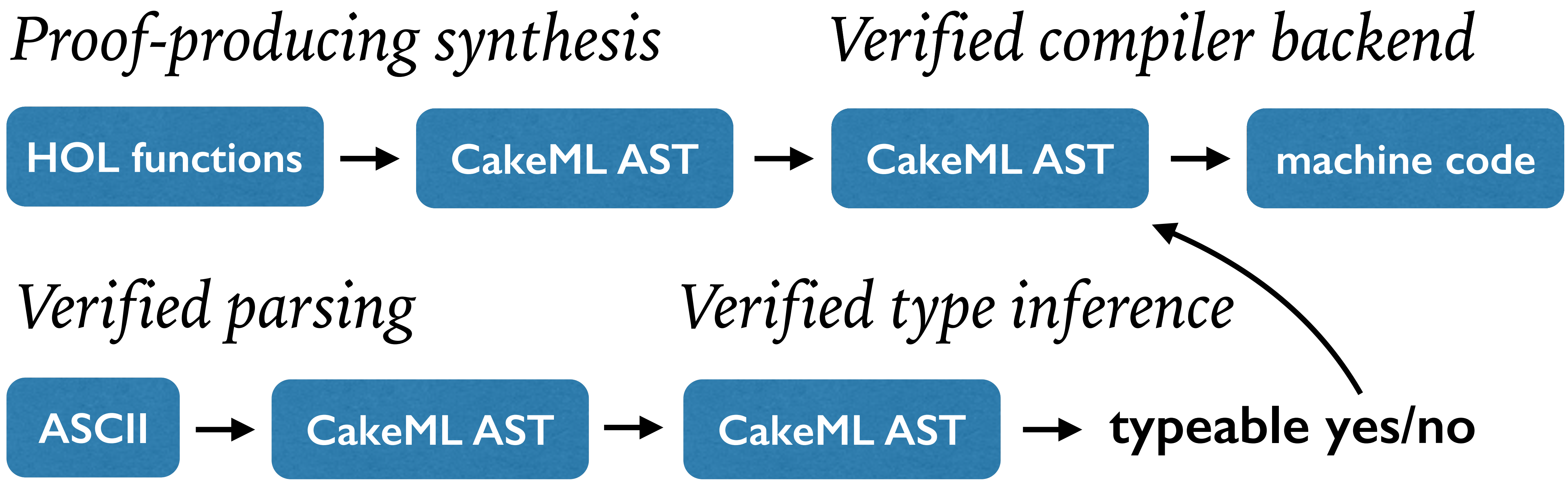
implementation in ML

implementation in machine code

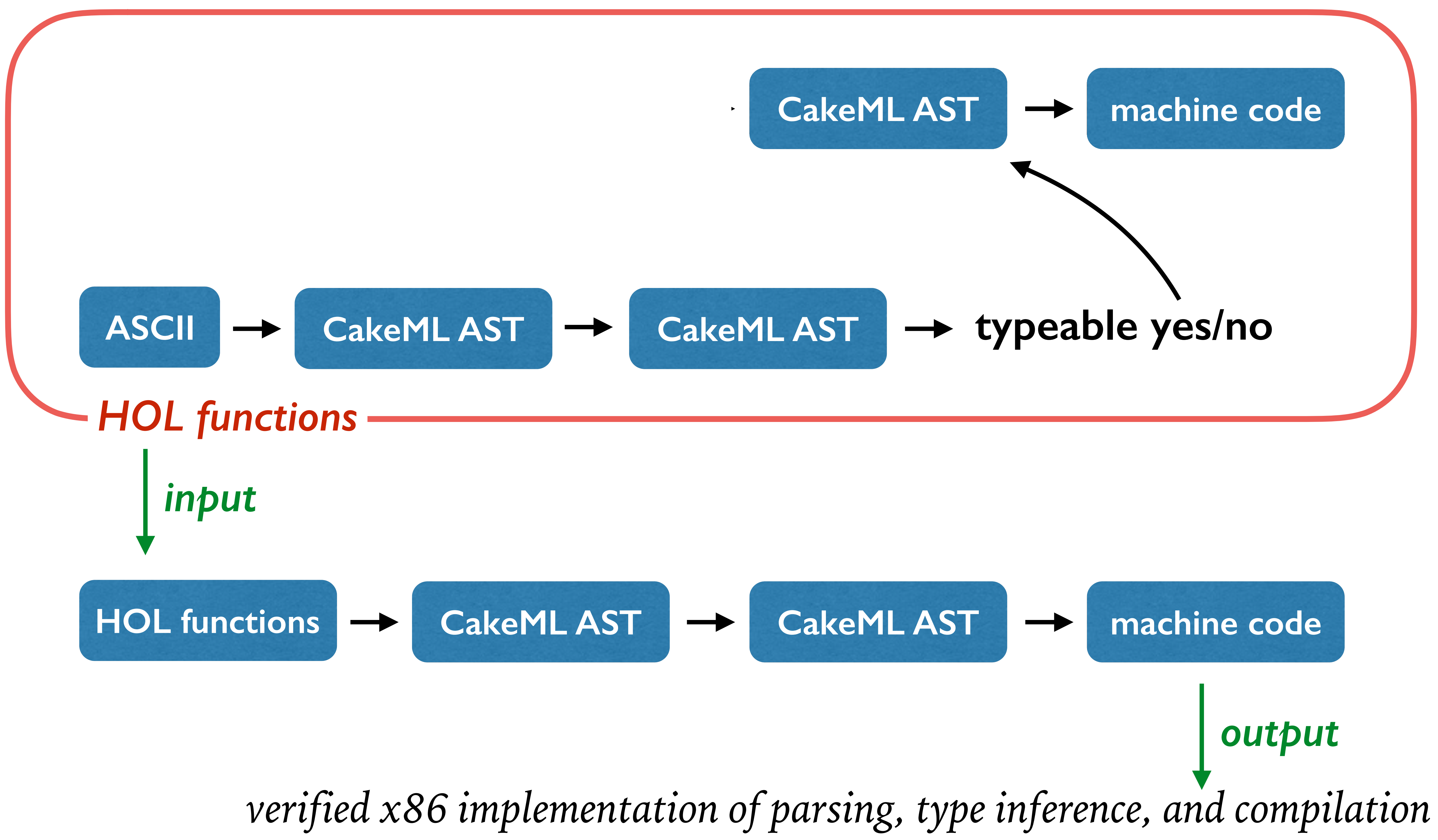
interactive call in read-eval-print loop runtime

the thing that is verified

Intuition for Bootstrapping

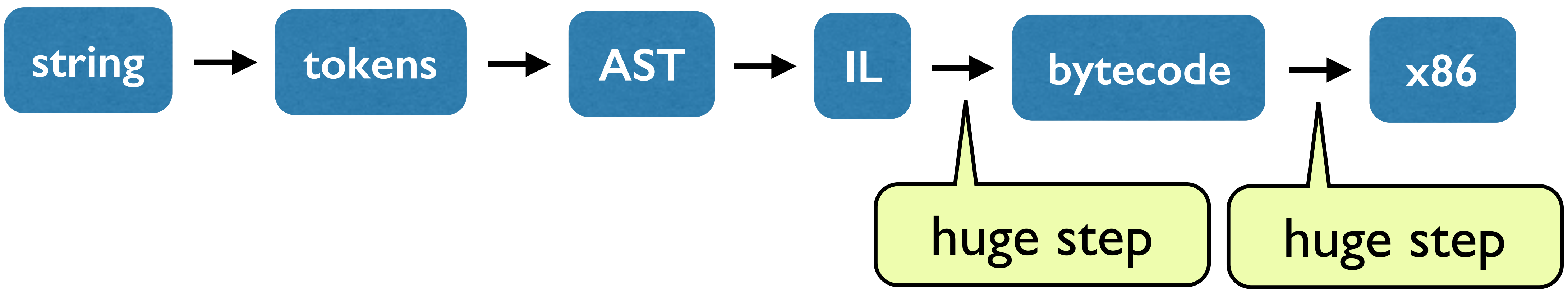


Intuition for Bootstrapping



Version 1 as in POPL'14

Compiler phases:



Bytecode simplified proofs of read-eval-print loop, but made optimisation impossible.

Almost no optimisations possible…

Poor design.

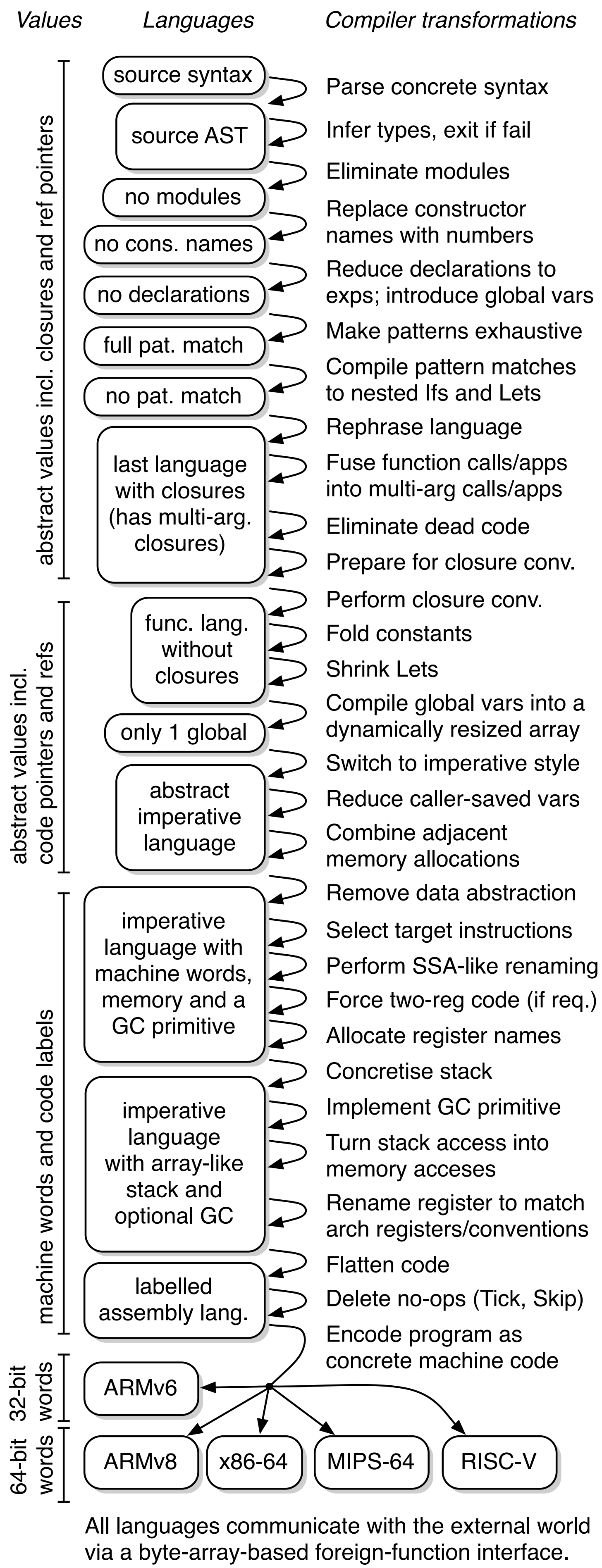
Version 2

Goals:

Design compatible with optimisations.

Acceptable performance.

Strategy: take inspiration from OCaml compiler (for some parts).



(next slides will zoom in)

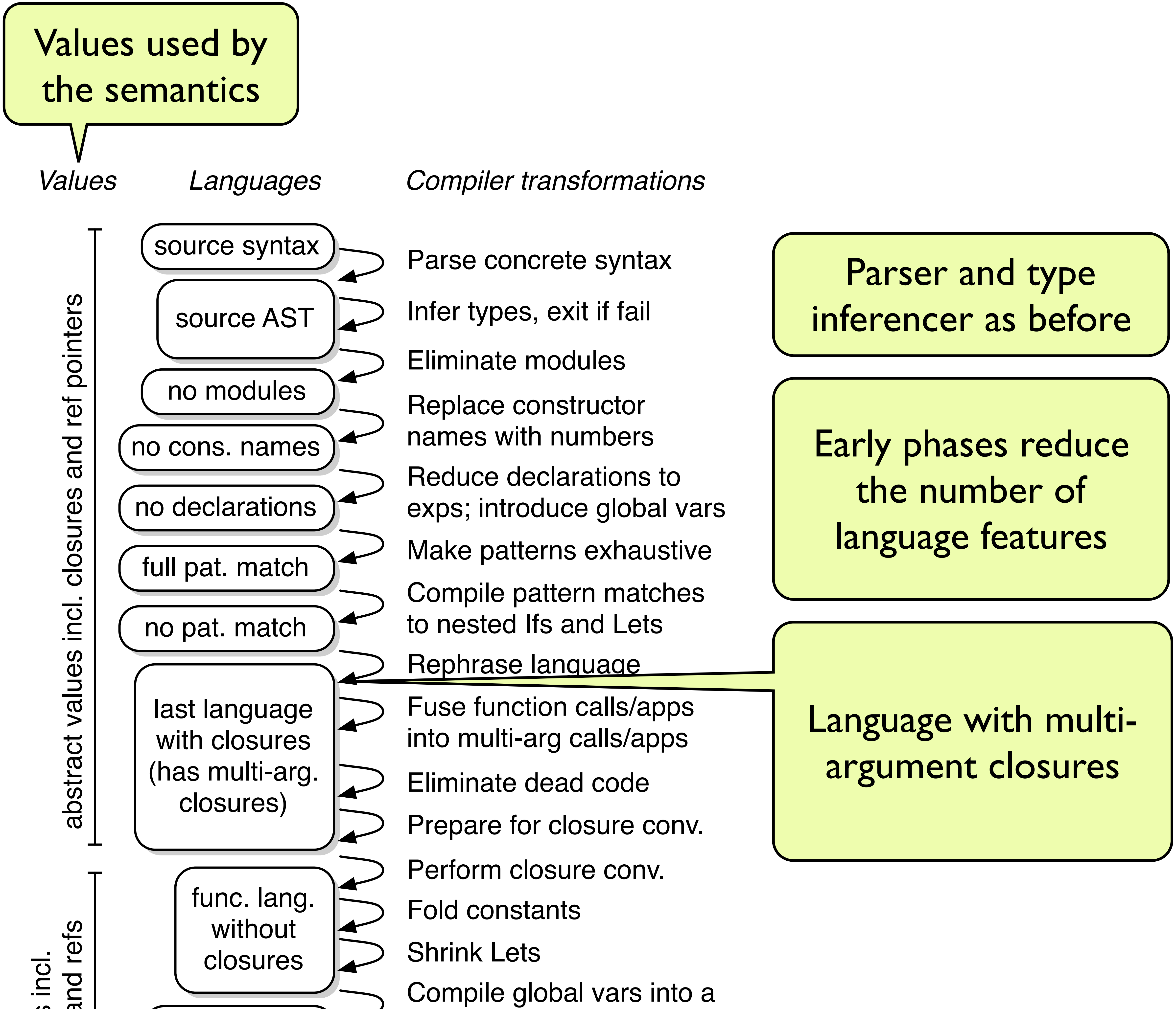
Result:

12 intermediate languages (ILs)

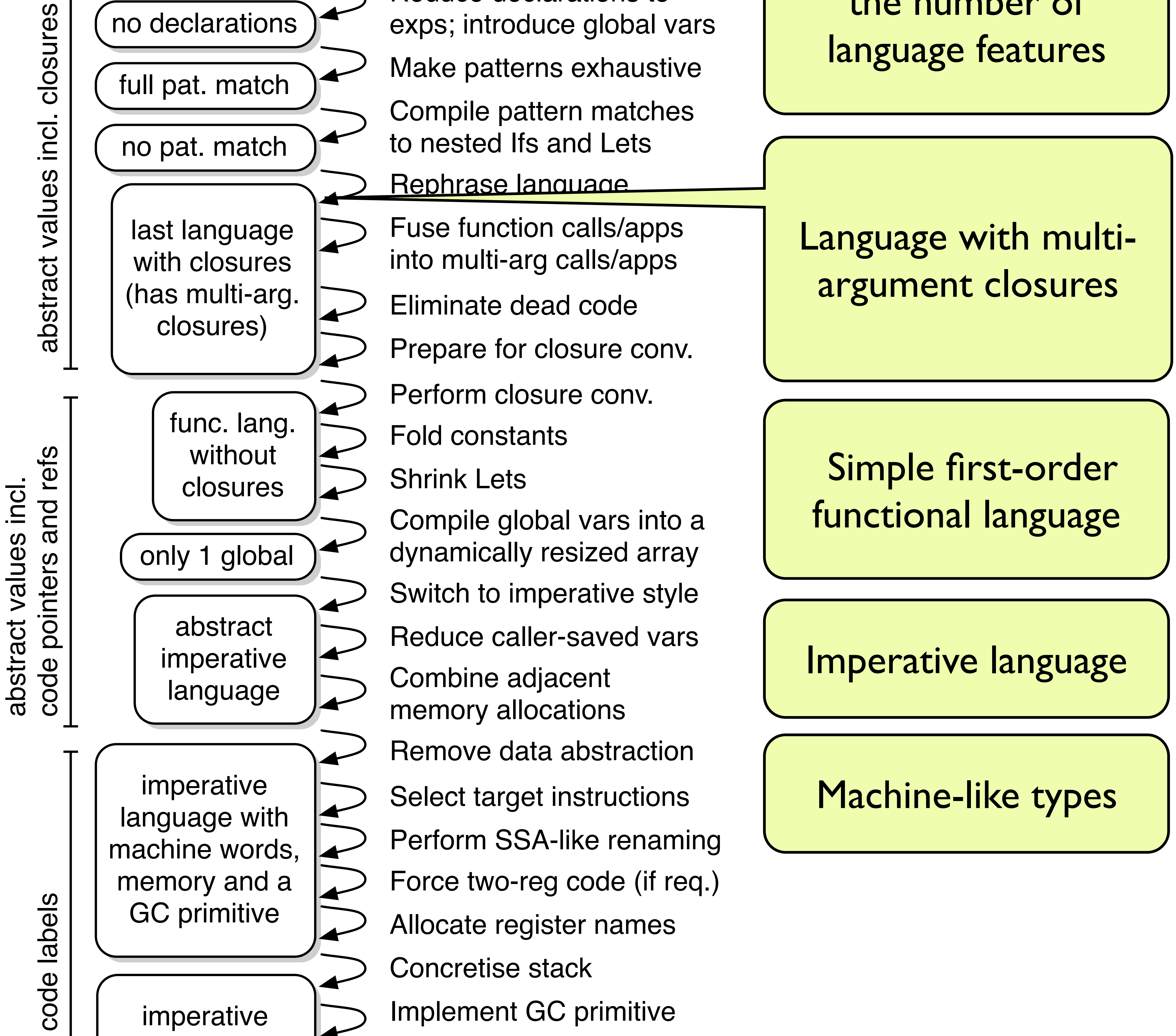
and many within-IL optimisations

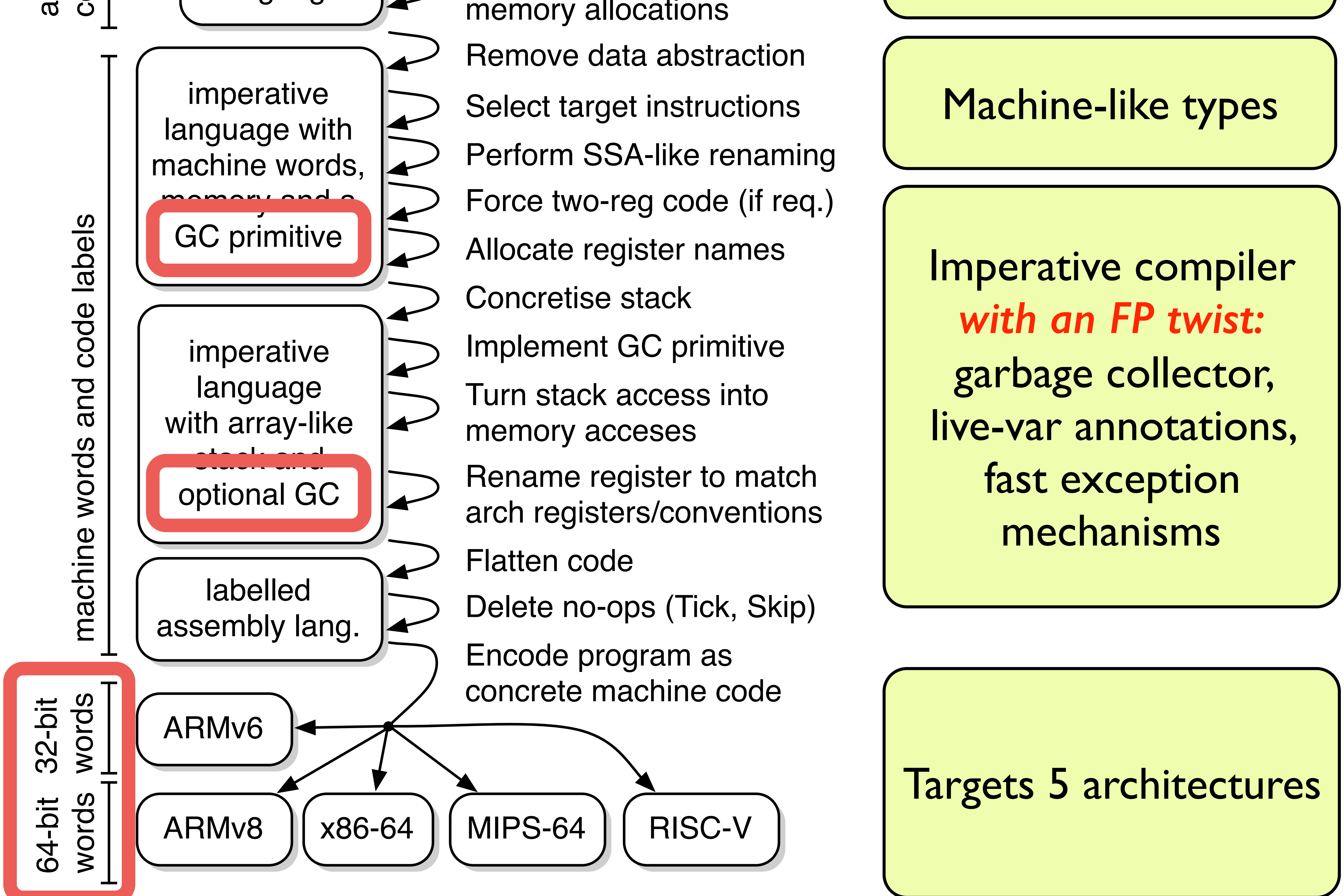
each IL at the right level of abstraction

for the benefit of proofs and compiler implementation



Values used by the semantics
Values
Languages
Compiler transformations
abstract values incl. closures and ref pointers
source syntax
Parse concrete syntax
source AST
Infer types, exit if fail
Eliminate modules
no modules
Replace constructor names with numbers
no cons. names
Reduce declarations to exps; introduce global vars
no declarations
Make patterns exhaustive
full pat. match
Compile pattern matches to nested Ifs and Lets
no pat. match
Rephrase language
last language with closures (has multi-arg. closures)
Fuse function calls/apps into multi-arg calls/apps
Eliminate dead code
Prepare for closure conv.
Perform closure conv.
func. lang. without closures
Fold constants
Shrink Lets
Compile global vars into a
Parser and type inferencer as before
Early phases reduce the number of language features
Language with multi-argument closures


abstract values incl. closures
abstract values incl. code pointers and refs
code labels
no declarations
full pat. match
no pat. match
last language with closures (has multi-arg. closures)
func. lang. without closures
only 1 global
abstract imperative language
imperative language with machine words, memory and a GC primitive
imperative
exps; introduce global vars
Make patterns exhaustive
Compile pattern matches to nested Ifs and Lets
Rephrase language
Fuse function calls/apps into multi-arg calls/apps
Eliminate dead code
Prepare for closure conv.
Perform closure conv.
Fold constants
Shrink Lets
Compile global vars into a dynamically resized array
Switch to imperative style
Reduce caller-saved vars
Combine adjacent memory allocations
Remove data abstraction
Select target instructions
Perform SSA-like renaming
Force two-reg code (if req.)
Allocate register names
Concretise stack
Implement GC primitive
the number of language features
Language with multi-argument closures
Simple first-order functional language
Imperative language
Machine-like types



All languages communicate with the external world via a byte-array-based foreign-function interface.

Some details

Closure representation:

Closures are values with a code pointer:

Block closure_tag
([CodePtr ptr; Number arg_count] @ $free\_var\_vals$)

For mutually recursive closures:

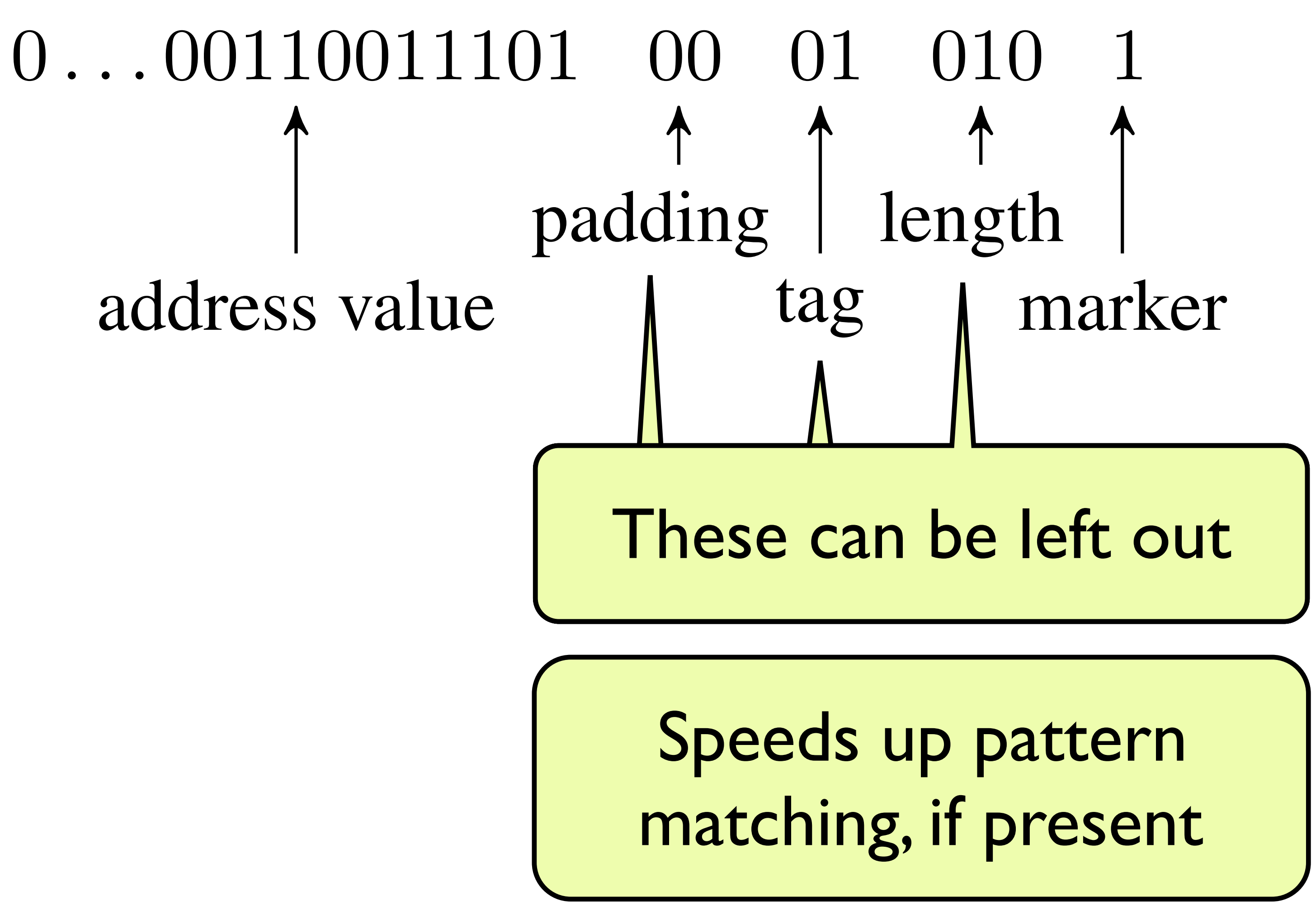
Block closure_tag
[CodePtr ptr; Number arg_count; RefPtr ref_ptr]

expected number of arguments
(multi-argument closures)

More details

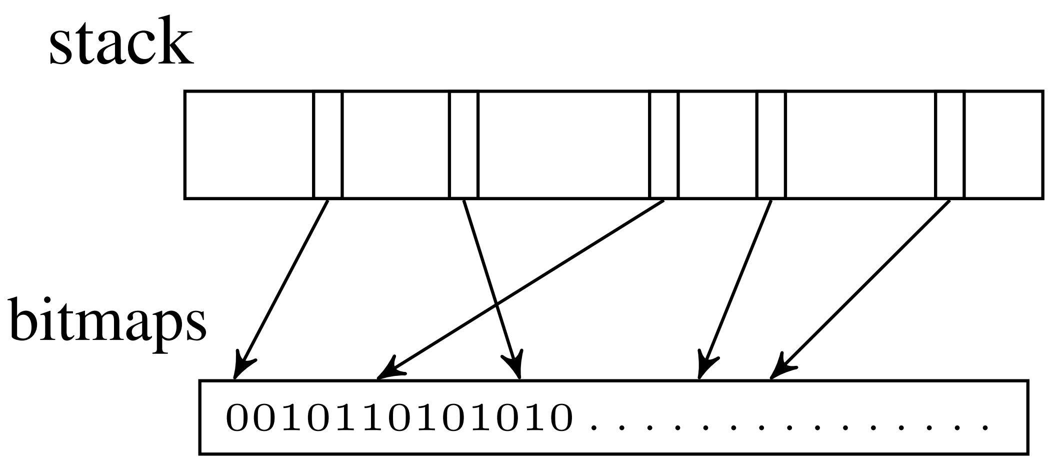
Configurable data representation

Example pointer value:

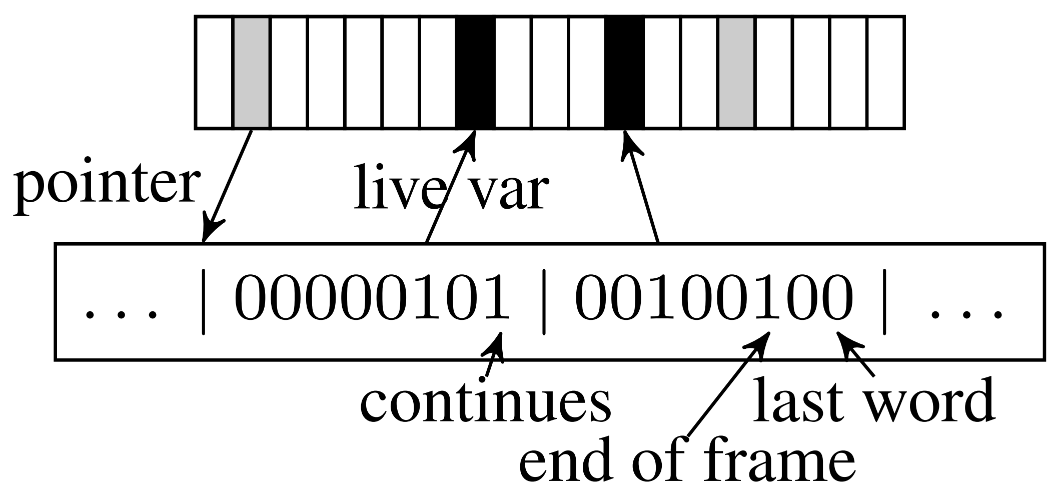


Even more details

Stack contains information about live vars for the GC



Details of one stack frame:



Semantics & Proofs

Semantics

Each intermediate language has a formal semantics.

We define these using a *functional big-step style* (ESOP'16) where the semantics is an evaluation function in logic

Extract of abstract first-order lang:

evaluate ([Var n], env, s) =
  if $n <$ len env then (Rval [nth n env], s)
  else (Rerr (Rabort Rtype_error), s)

evaluate ([If x_1 x_2 x_3], env, s) =
  case evaluate ([x_1], env, s) of
    (Rval vs, s_1) ⇒
      if Boolv true = hd vs then evaluate ([x_2], env, s_1)
      else if Boolv false = hd vs then evaluate ([x_3], env, s_1)
      else (Rerr (Rabort Rtype_error), s_1)
  | (Rerr e, s_1) ⇒ (Rerr e, s_1)

Top-level observable FFI semantics defined using evaluate.

Proof

Proof styles:

Standard induction on evaluation function

✓ proofs in direction of compilation

✓ no co-induction needed for divergence pres. (ESOP'16)

Untyped logical relation (ind. on compile function)

Each part of the compiler preserves obs. semantics:

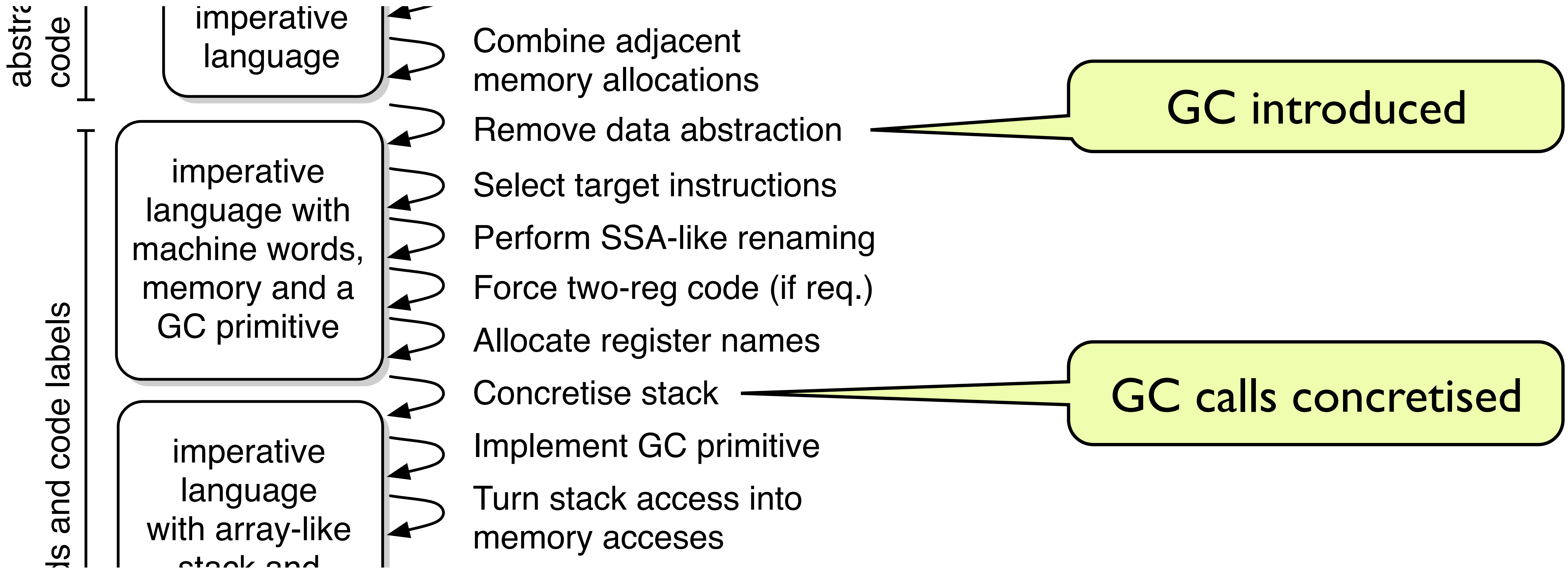
$\vdash$ compile $\mathit{config}\ \mathit{prog} = \mathit{new\_prog}\ \wedge$
syntactic_condition $\mathit{prog}\ \wedge$
Fail $\notin$ semantics $\mathit{ffi}\ \mathit{prog} \Rightarrow$
semantics $\mathit{ffi}\ \mathit{new\_prog} \subseteq$
extend_with_resource_limit (semantics $\mathit{ffi}\ \mathit{prog}$)

type-safe source implies this

due to out-of-memory error

Difficult cases

GC and register allocator interaction



Solution: we use a semantics that allows reordering of stack variables.

Size, Effort, Speed

Compiler Size: 6 000 lines of function definitions
(excludes target-specific instruction encoders & config)

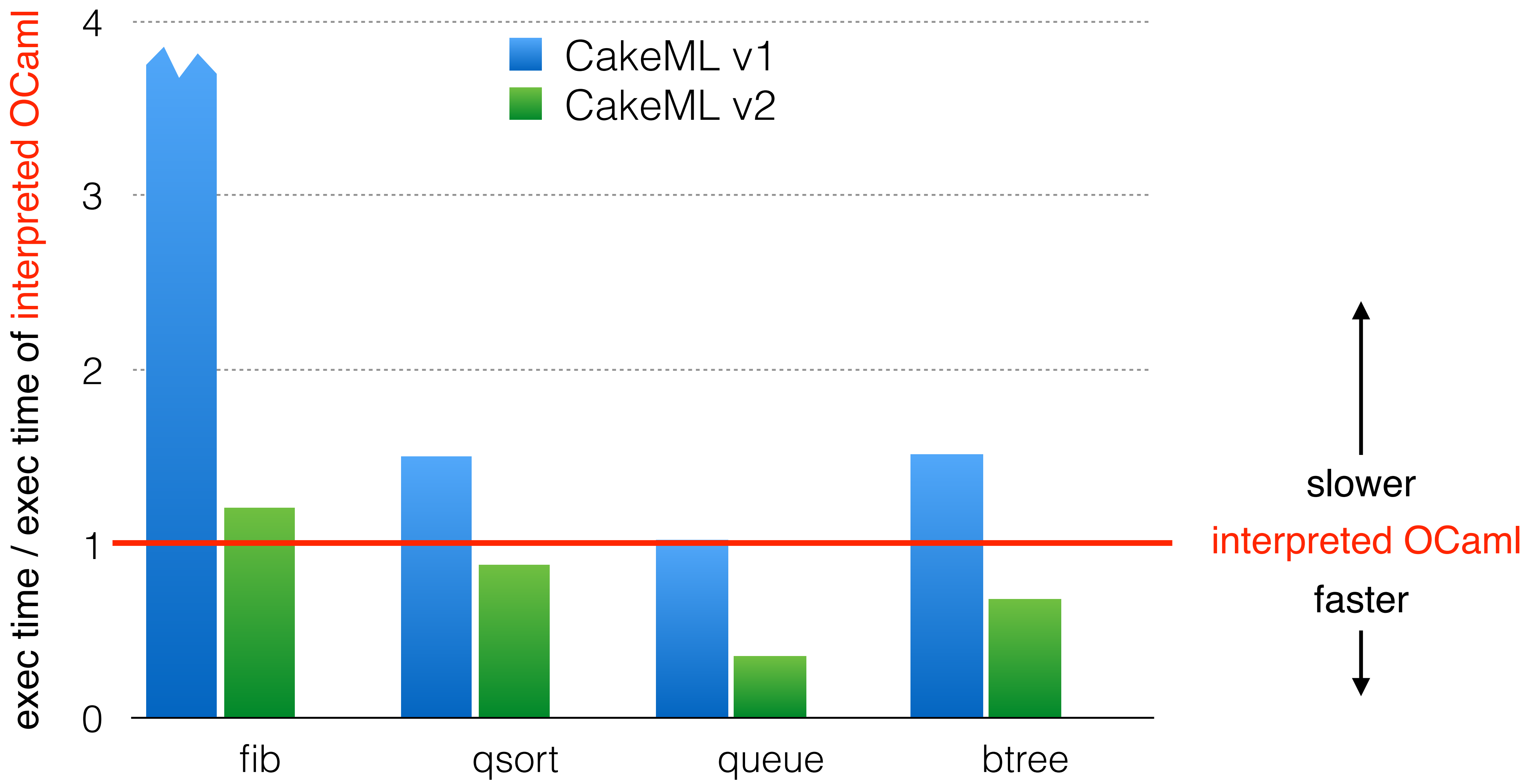
Proof Size: 100 000 lines of HOL proof script

Effort: 6 people, 2 years, but not full time

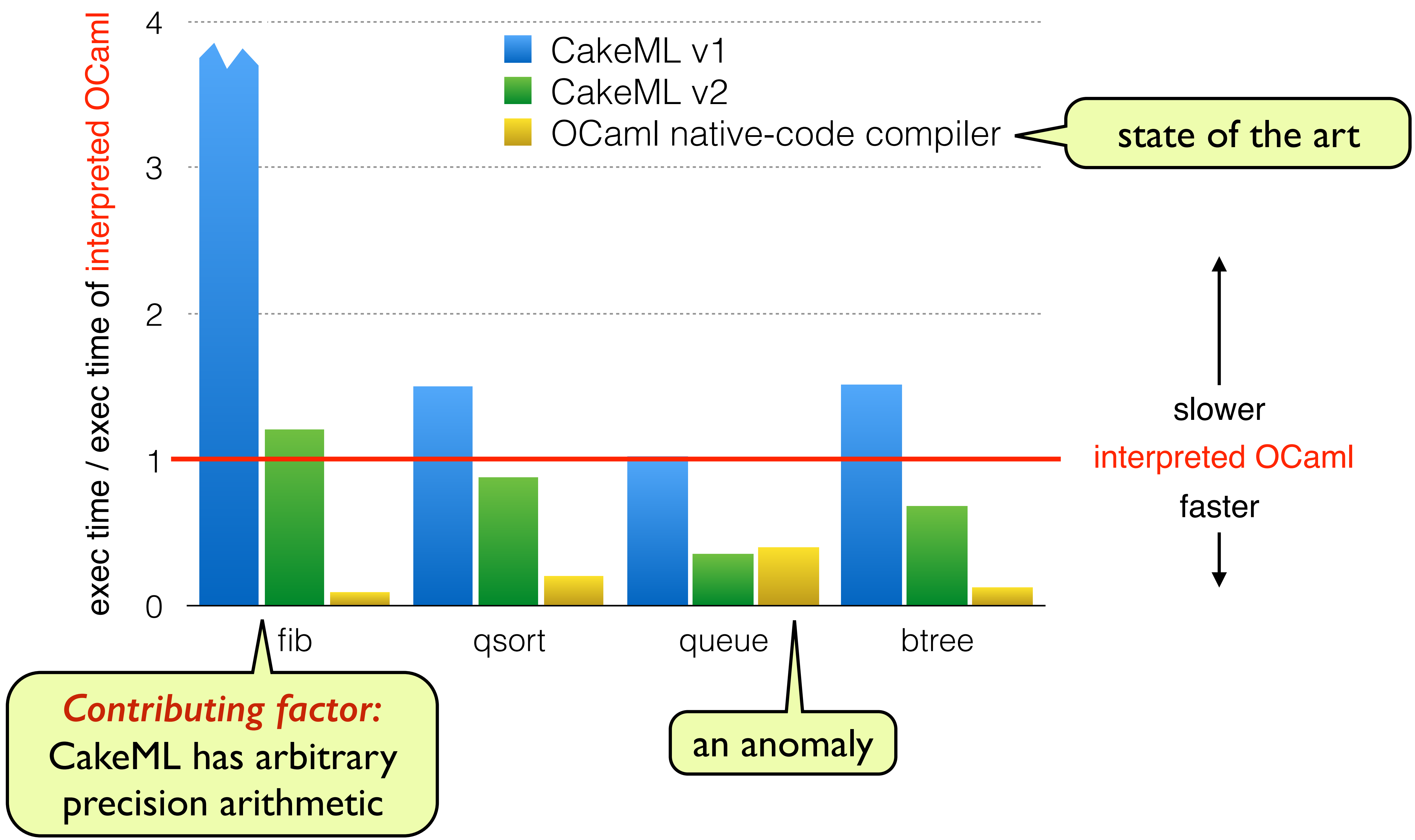
Speed: next slide…

(Numbers up-to-date as of April 2016)

Simple Benchmarks



Simple Benchmarks



Simple Benchmarks

Why?

Version 1 *can compile big programs* (in-logic)

Version 2 *in-logic* evaluation is *too slow* for large examples

we are working to improve this

why not outside?

Immediate future work

unknown

```
fun map f [] = []
  | map f (x::xs) = f x :: map f xs;

val list_add1 = map (fn n => n + 1);
```

Any app of a *known* function needs to be optimised to a *fast procedure call*.

Inlining should produce a copy of map *specialised* for `fn n => n+1`

CakeML

This talk: *New compiler's design* compatible with *optimisations*

Big-picture: *Ecosystem* around a clean formalised ML language

Why? *End-to-end verification, and end-to-end verified applications*

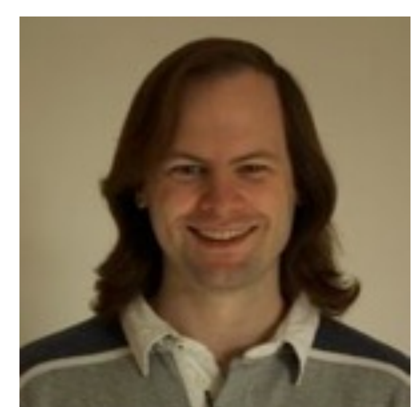
Questions?


Magnus Myreen


Yong Kiam Tan


Ramana Kumar


Anthony Fox


Scott Owens


Michael Norrish