CAKEML

A Verified Implementation of ML

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CakeML Logo: Trần Tiến Dũng

Dimensions of Compiler Verification

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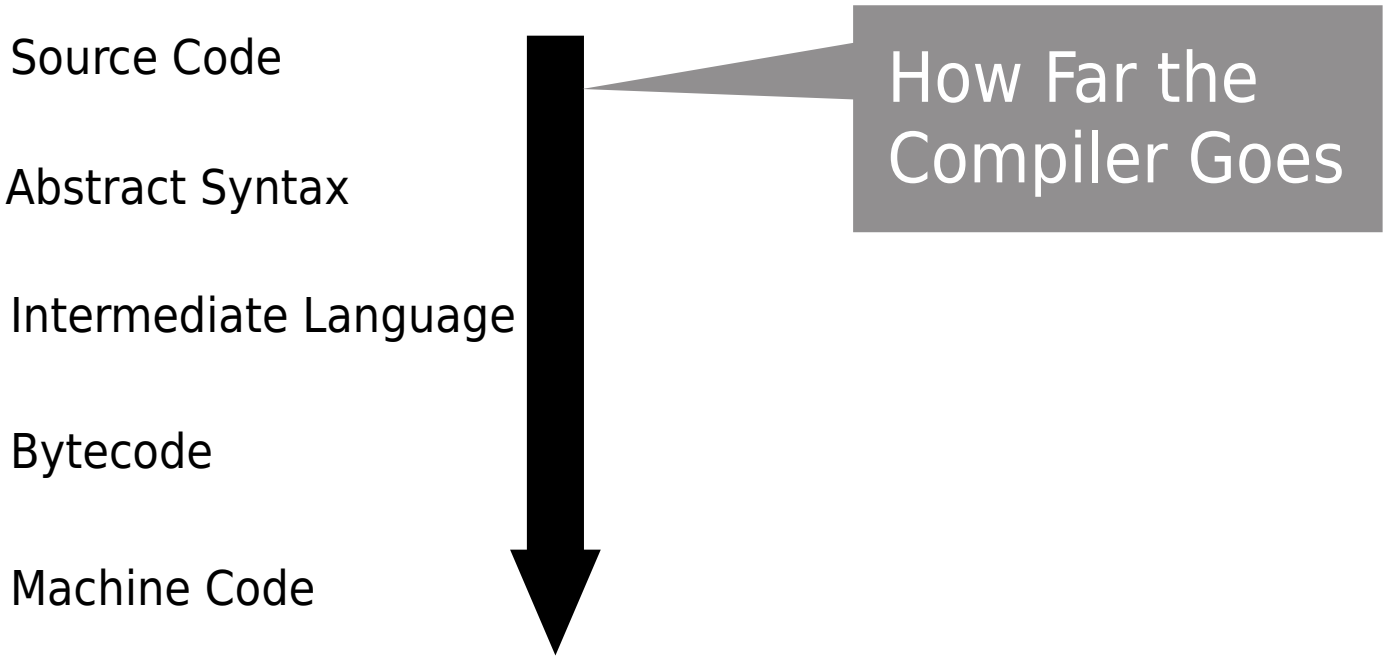

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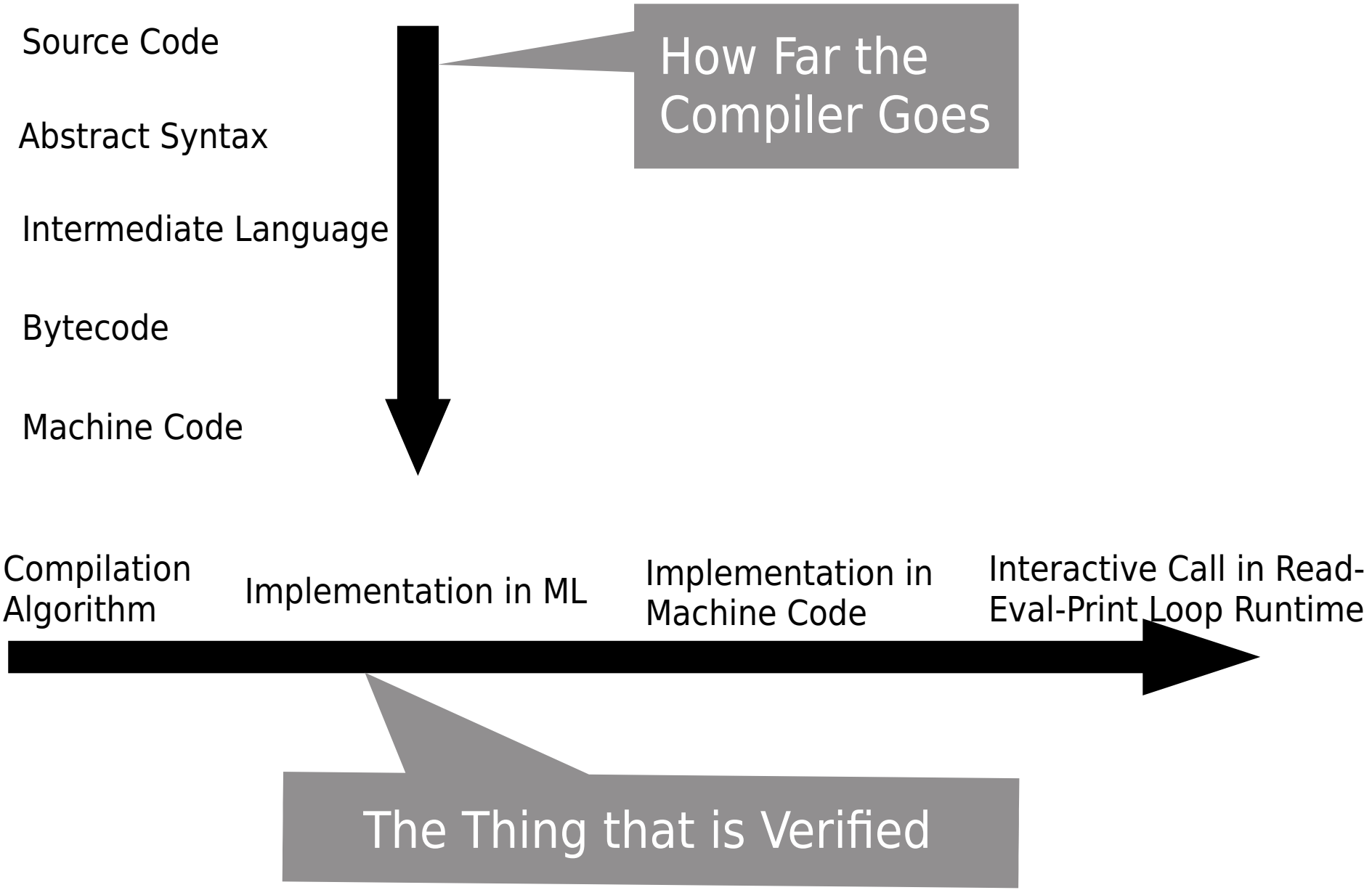

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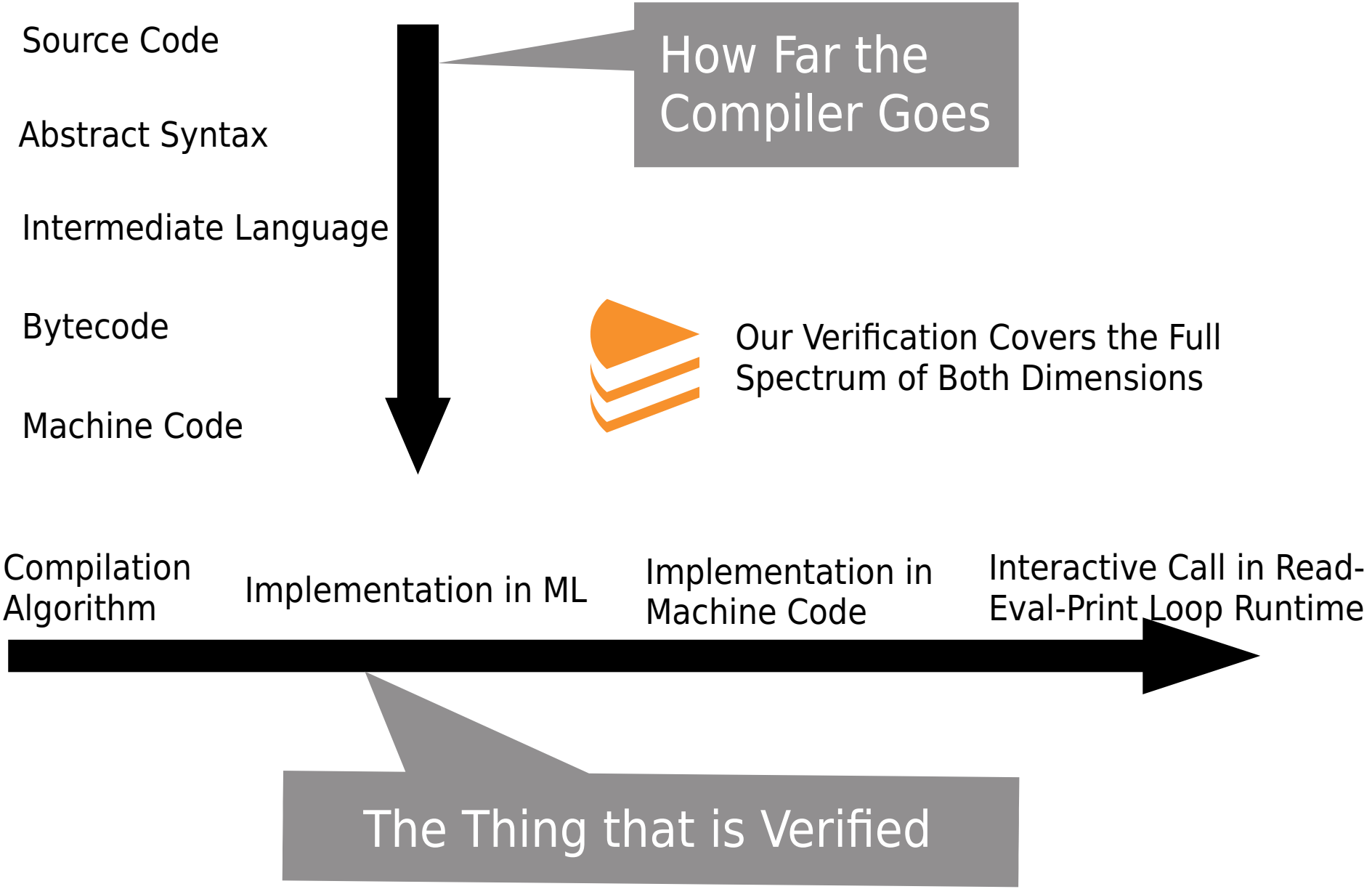

The Size of the Language

CakeML, the language

= Standard ML without I/O or functors

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i.e., most everything else:

- ✔ higher-order functions,
- ✔ mutual recursion and polymorphism,
- ✔ datatypes and pattern matching,
- ✔ references and exceptions,
- ✔ modules and signatures

Artefacts

Proof Techniques

Artefacts

Specifications

Verified Algorithms

Verified Executable

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Interactive Proof

x86 Synthesis

ML Synthesis

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including new inductive approach to divergence preservation

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including new inductive approach to divergence preservation

main new technique: use verified compiler to produce verified implementation

Specifications and Verified Algorithms

All Defined and Proved in HOL

Lexing and Parsing

- Context-Free Grammar for ML
- Executable Lexer Specification
- Parsing-Expression-Grammar (PEG) Parser
  (inductive evaluation relation, plus executable interpreter for PEGs)
- Soundness and Completeness
  (induction on length of token list/parse tree and non-terminal rank)
- Deterministic, hence CFG is unambiguous

Operational Semantics

- Big-step evaluation relation
- Environment semantics (closures)
- Runtime type errors (stuck = divergence)
- Also: small-step CEK machine
  (for type soundness proof, and defining divergence)
- Read-eval-print loop semantics

Type Inference

- Based on Algorithm J
- Purely functional (state-exception monad)
- Proved sound wrt declarative type system
- Re-use existing work on verified unification

Compilation (1)

- Translation to Intermediate Language:
  - de Bruijn indices
  - Pattern-match compilation
  - Closure conversion
  - Big-step operational semantics
- Next: translation to Bytecode

Compilation (2)

- <Bytecode stuff> <data refinement>
- <inductive proof>

Divergence Preservation

- Add optional clock to semantics and bytecode
- Totality ensures: with clock, every program either yields a result or times out
- Extend inductive compiler correctness proof: timeout in semantics ⇒ timeout in bytecode
- Deterministic bytecode; if it times out for every clock, it diverges without the clock

Translation to Machine Code

- <x86 machine model>
- <machine code Hoare logic>
- <x64 heap invariant>
- <extension of Hoare logic for divergence>

Runtime Algorithms

- Garbage collector, allocator
- Bignum library
- Main loop

Producing a Verified Implementation

Machine Code Synthesis

- <Validating compilation via proof-producing decompilation>
- Used for: the bits of runtime around the compiler (gc, bignum, etc.)

ML Synthesis

- Proof-producing translation from shallow embedding to deep embedding
- <something about EVAL>
- <example of shallow vs deep>

Bootstrapping

- <four schematic theorems>

Data

Performance

Effort

<conclusion slide>
https://cakeml.org

Bonus Slides

Correctness Theorem Statement