This document uses the slide template from the “Interactive Theorem Proving Course” by Thomas Tuerk (`https://www.thomas-tuerk.de`):
`https://github.com/thtuerk/ITP-course`

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Interactive Theorem Proving and Program Verification
Lecture 9

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Based on slides by Thomas Tuerk

Part XVI

Obtaining Verified Programs

Verifying Executable Code with ITPs

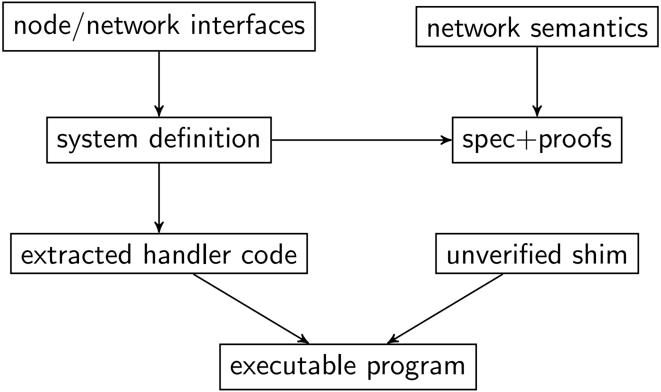
Many options available:

- using code extraction (to SML, OCaml, Haskell, ...)
- reasoning directly about deeply embedded "real" programs using their semantics
- validating compiled binaries
- using a verified compiler
- ...

Trusted Computing Bases (TCB)

- what is verified vs. what is trusted?
- TCB originally from security (and adversarial)
- verification TCB typically includes at least
  - hardware (processor, ISA, ...)
  - operating system
  - low-level system libraries
- small TCB is (nearly) always preferable

Example: Verified Distributed System



Code Extraction

- Standard ML extraction in HOL4 (EmitML module)
- OCaml and Haskell in Coq
- Standard ML, Scala, Haskell in Isabelle/HOL

EmitML Example

```
open EmitML basis_emitTheory;

val _ = eSML "my_theory" [
  DATATYPE mydata,
  DEFN myfun1_def,
  DEFN myfun2_def,
  DEFN myfun3_def
];
```

Translation Validation of Binaries

- extraction is not guaranteed (via machine-checked proofs) to preserve program semantics
- a translation validation approach can establish that generated binary adheres to source language semantics
- used to analyze binaries generated by gcc for the seL4 operating system kernel
- general approach that can be used for other tasks than compilation

Verified Compilation

- verified compilers can directly produce machine code that is guaranteed be consistent with program meaning
- needed: hardware ISA semantics, source language semantics
- usually constructed as translations between many intermediate languages
- examples: CakeML, CompCert

Verified Compilation Top-Level Theorem

Any binary produced by a successful evaluation of the compiler function will either

- behave exactly according to the observable behaviour of the source semantics, or
- behave the same as the source up to some point at which it terminates with an out-of-memory error.

Typical assumptions:

- external world doesn't modify allocated memory
- external procedures called by program are well-behaved

Purely Functional vs. Imperative Code

- purely functional code usually verified by rewriting (lightweight)
- imperative code usually needs Hoare logic verification (heavyweight)
- reasoning about heaps is a lot of work (even with separation logic)
- conjecture (X. Leroy): purely functional programs are the most straightforward path to verified code

Part XVII

Introduction to CakeML

CakeML in a Nutshell

- bootstrapping verified compiler for SML-like language, implemented in HOL4
- can generate machine code for MIPS, x86, x86-64, ARMv8, RISC-V
- source and pre-compiled CakeML compatible with HOL4 Kananaskis-13 available online:

  `https://github.com/CakeML/cakeml/releases/download/v1009/cake-x64-64.tar.gz`

  `https://github.com/CakeML/cakeml/archive/v1009.tar.gz`

Properties of the CakeML Language

- impure language in the SML family
- eagerly evaluated
- semantics given in functional big-step style
- supports IO and FFI
- all integers are unbounded

Syntax of CakeML vs. Standard ML

- CakeML has curried Haskell-style constructor syntax
- constructors in CakeML must begin with an uppercase letter
- constructors must be fully applied
- alpha-numeric variable and function names begin with a lowercase letter
- CakeML lacks SML's records, functors, open and (at present) signatures
- CakeML capitalises `True`, False and `Ref`

Semantics of CakeML vs. Standard ML

- right-to-left evaluation order
- CakeML has no equality types
- semantics of equality is different from SML and OCaml
- multi-argument functions

Example CakeML Programs

Hello World:

```
print "Hello world!\n";
```

Fibonacci with argument from CLI:

```
fun fiba i j n = if n = 0 then i else fiba j (i+j) (n-1);
(print (n2s (fiba 0 1 (s2n (hd (CommandLine.arguments())))));
 print "\n")
 handle _ => print_err ("usage: " ^ CommandLine.name() ^ " <n>\n");
```

CakeML List Functions

```
fun foldl f e xs =
  case xs of [] => e
  | (x::xs) => foldl f (f e x) xs;

fun reverse xs =
  let
    fun append xs ys =
      case xs of [] => ys
      | (x::xs) => x :: append xs ys;
    fun rev xs =
      case xs of [] => xs
      | (x::xs) => append (rev xs) [x]
  in
    rev xs
  end;
```

Example Using CakeML as Compiler

Download the pre-compiled CakeML, and put “hello world” program in `hello.cml`:

```
$ make hello.cake
$ ./hello.cake
Hello world!
```

Compiler takes 20+ hours to bootstrap!

Verifying Programs Using CakeML

- imperative programs handled via monads in HOL4
- proof-producing synthesis in HOL4 via **translator**
- post-hoc verification using separation logic

See CakeML journal paper for overview:
`https://cakeml.org/jfp19.pdf`