Compiler Construction

Lecture 16

Bootstrapping

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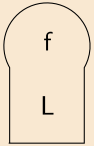
Recommended book

Chapter 13 of
Basics of Compiler Design
Torben Ægidius Mogensen
`http://hjemmesider.diku.dk/~torbenm/Basics/`

Notation

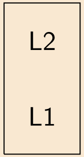
Notation: programs, interpreters, machines

A program



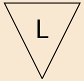
Computes function f
written in language L

An interpreter



Interprets language L2
written in language L1

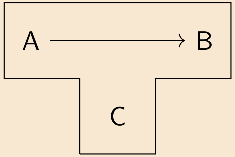
A machine



Executes code
in language L

Notation: compilers

A compiler

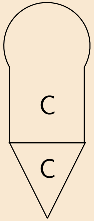


Translates language A into language B
Written in language C

Examples

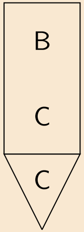
Executing programs

To execute a program



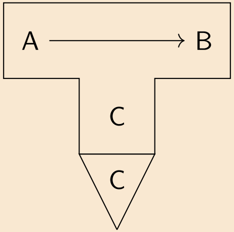
we run it on a machine

To execute an interpreter



we run it on a machine

To execute a compiler



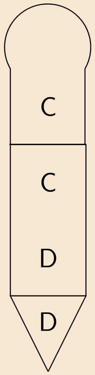
we run it on a machine

Interpreting a program

Run a program
written in language C

on an interpreter for C
written in language D

on a D machine



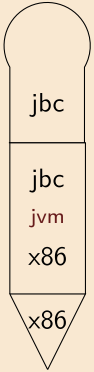
(Note: the languages must match)

Interpreting a Java program

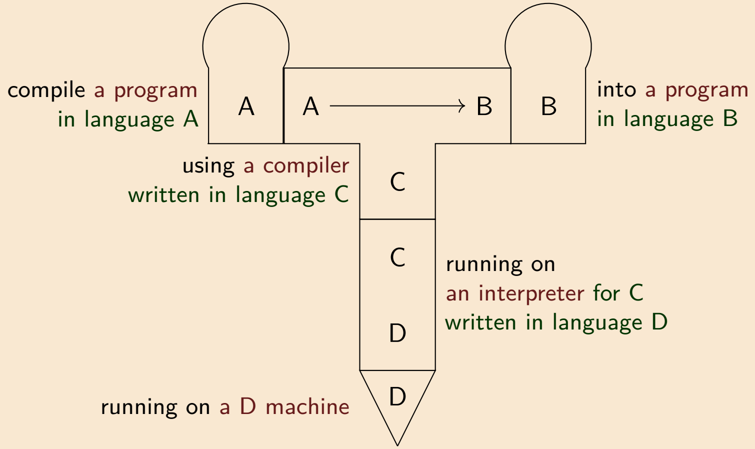
Run a program
written in Java byte code

on an interpreter for Java byte code
written in x86 code

on a x86 machine



Running a compiler on an interpreter



Running javac on the JVM

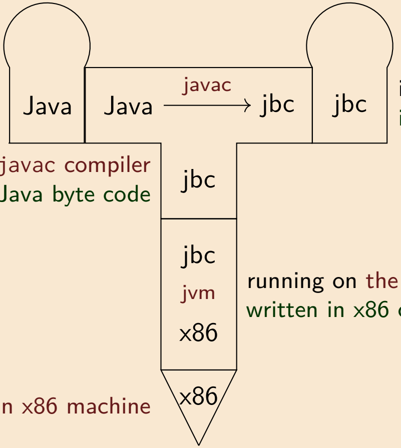
compile a program in Java

into a program in Java byte code

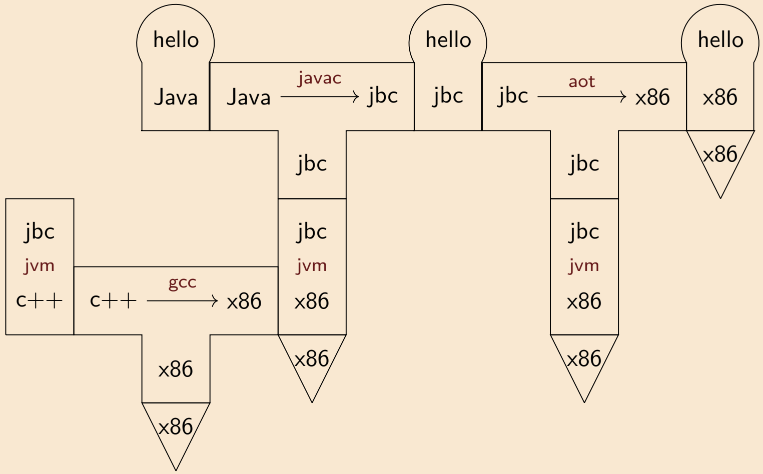
using the javac compiler written in Java byte code

running on the JVM written in x86 code

running on an x86 machine



Ahead-of-time compilation for Java

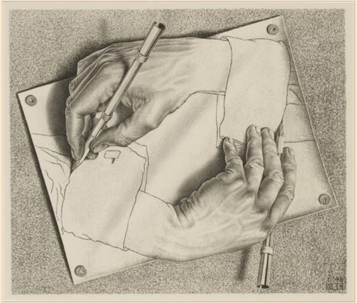


Thanks to David Greaves for the example

Compiling compilers

A puzzle

The OCaml compiler
is written in OCaml



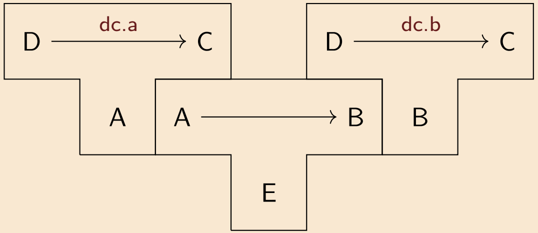
Puzzle: how was the compiler compiled?

Translating translators

Compilers can be translated, just like any other program:

a compiler from D to C in language A

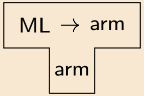
a compiler from D to C in language B



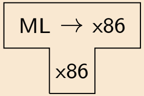
compile programs from A to B

Porting a compiler to a new platform

We have:
a compiler from ML to arm
that runs on arm



We want:
a compiler from ML to x86
that runs on x86



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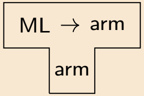

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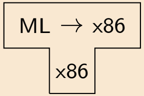
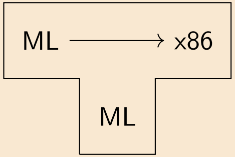
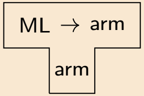


1. write an ML-to-x86 compiler in ML



Porting a compiler to a new platform

We have: a compiler from ML to arm that runs on arm



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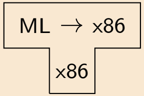
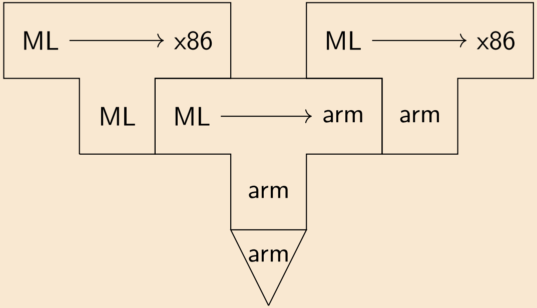


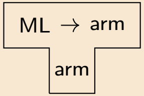
1. write an ML-to-x86 compiler in ML

2. compile the compiler for arm



Porting a compiler to a new platform

We have:
a compiler from ML to arm
that runs on arm



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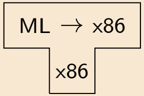
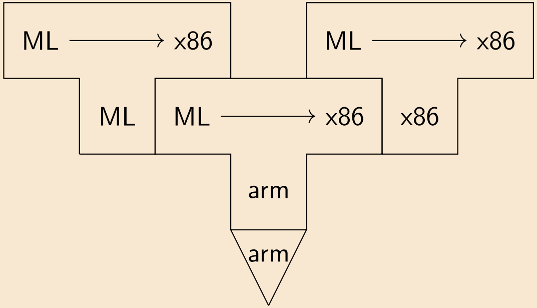


1. write an ML-to-x86 compiler in ML
2. compile the compiler for arm
3. run the compiler on arm to compile itself



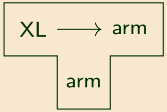
Full bootstrap

Half and full bootstraps

Previous example: *half bootstrap* (needs existing compiler for the language).

New example: *full bootstrap* (no existing ML compiler for the language)

We want:
a compiler from **XL** to arm
that runs on arm



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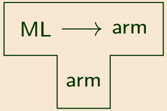

Full bootstrap

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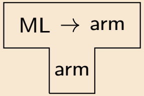

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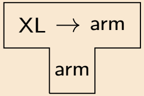

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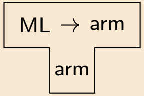

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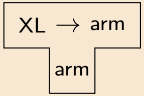
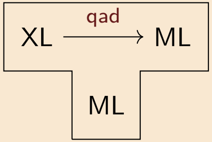


1. write a quick-and-dirty (QAD)
   XL-to-ML compiler in ML



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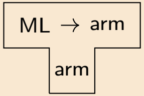

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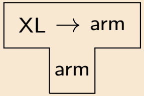
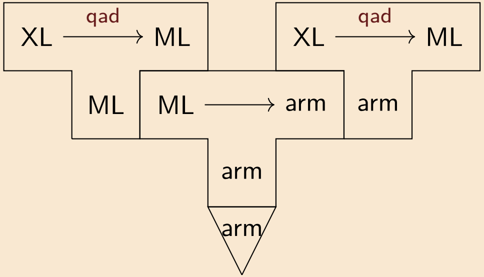


1. write a quick-and-dirty (QAD) **XL-to-ML** compiler in ML

2. compile the QAD compiler for arm



Full bootstrap

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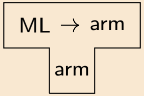

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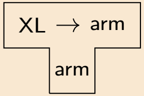

1. write a quick-and-dirty (QAD)
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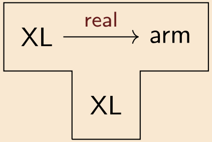
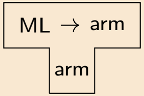
2. compile the QAD compiler for arm

3. Write a real **XL-to-arm** compiler in **XL**



Full bootstrap

We have: a compiler from ML to arm that runs on arm



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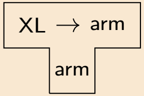
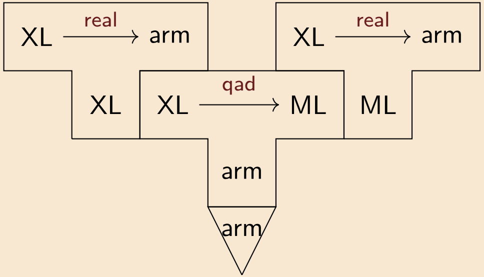
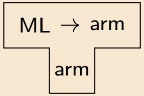


1. write a quick-and-dirty (QAD) **XL-to-ML** compiler in ML
2. compile the QAD compiler for arm
3. Write a real **XL-to-arm** compiler in **XL**
4. Use the QAD compiler to compile the real compiler to ML



Full bootstrap

We have: a compiler from ML to arm that runs on arm



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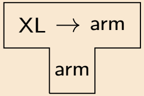

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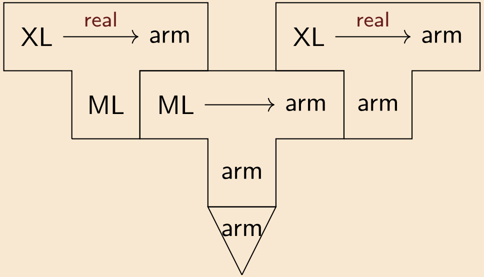
5. Compile the resulting ML program to arm



Full bootstrap

We have:
a compiler from ML to arm
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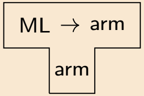

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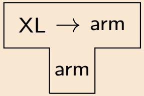

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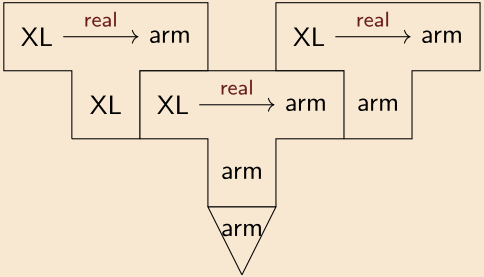
2. compile the QAD compiler for arm
3. Write a real **XL-to-arm** compiler in **XL**
4. Use the QAD compiler to compile the real compiler to ML
5. Compile the resulting ML program to arm
6. Use the generated compiler to compile itself


XL $\xrightarrow{\text{real}}$ arm
XL
XL $\xrightarrow{\text{real}}$ arm
XL $\xrightarrow{\text{real}}$ arm
arm
arm
arm

Observations

The *speed* of the quick-and-dirty compiler does not matter much
(We could even use a quick-and-dirty interpreter instead)

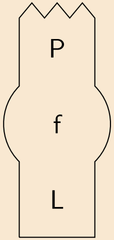
We don't need to give the quick-and-dirty compiler to users

Once the real compiler works,
we can discard the quick-and-dirty compiler altogether

Verified compilation

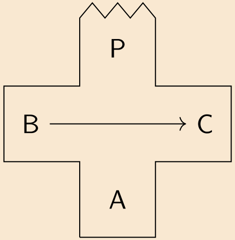
New notation: proofs of correctness

A verified program



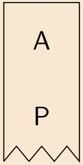
Computes function f
written in language L
with a proof in language P

A verified compiler



Translates language A into B
written in language C
with a proof in language P

A proof checker

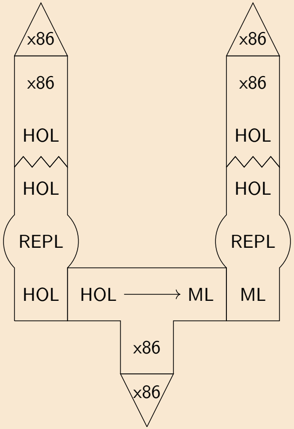


Checks proofs in language P
Written in language A

Thanks to Paul D'Souza for the extended notation and the example

Compiling the CakeML verified compiler: HOL $\rightsquigarrow$ ML

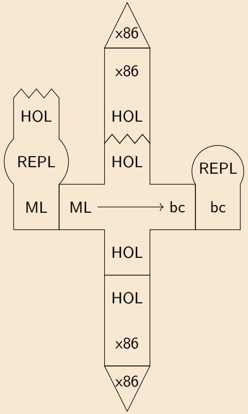
The CakeML REPL[1] is written in HOL and compiled to ML code + a proof



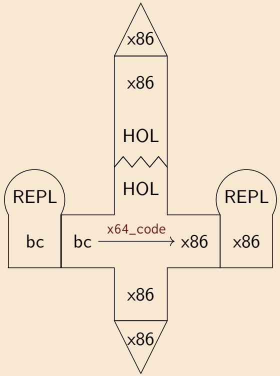
[1] read-eval-print loop

Compiling the CakeML verified compiler: ML $\rightsquigarrow$ x86

Next, the *verified* compiler compiles the REPL to bytecode



Finally, the bytecode is compiled



Theorem (abridged): the x86 REPL behaves according to the original specification

Trusting trust

Escaping characters

"The cutest program I ever wrote"
– Ken Thompson

(Reflections on Trusting Trust)

Aim: modify a compiler to compromise `login`

Warm up: teach a compiler about vertical tabs

C compilers have code to interpret escape sequences like `\n` in `"Hello, world\n`:

```
...
c = next();
if (c != '\\') return c;
c = next();
if (c == '\\') return '\\';
if (c == 'n') return '\n';
...
```

Q: how can we add support for vertical tabs `\v`?

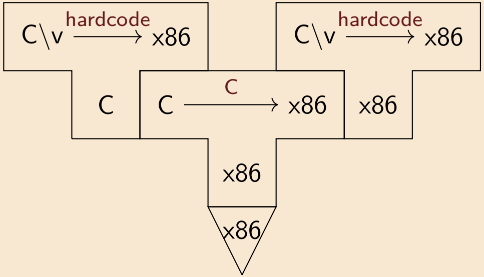
(Assume the C compiler is bootstrapped.)

Teaching the compiler about \v

Step 1: hard-code the ASCII code for `\v` in the compiler source:

```
c = next();
if (c == '\\') return '\\';
if (c == 'n') return '\n';
if (c == 'v') return 11;
...
```

Recompile the compiler source using the installed C compiler:


C\v $\xrightarrow{\text{hardcode}}$ x86
C
C $\xrightarrow{\text{C}}$ x86
C\v $\xrightarrow{\text{hardcode}}$ x86
x86
x86
x86

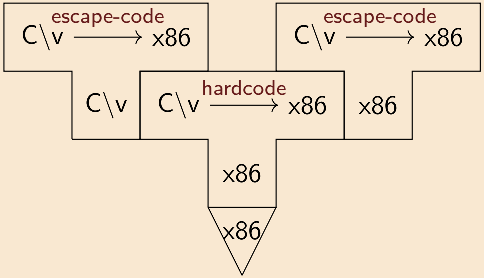
Now we have a C compiler that supports `\v` in C programs. Install it.

The compiler has learnt about \v

Step 2: modify the compiler source again to remove the hardcoded constant:

```
c = next();
if (c == '\\') return '\\';
if (c == 'n') return '\n';
if (c == 'v') return '\v';
...
```

Recompile the modified source using the freshly installed C compiler:



The C compiler has learnt to translate \v (but there's no record in the source!)

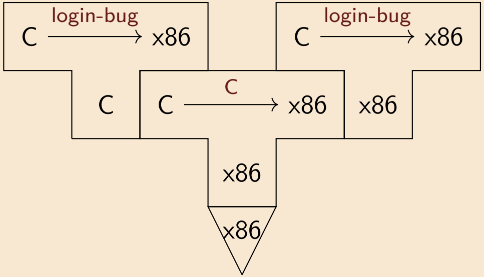
Teaching the compiler to insert backdoors

Plan: repeat the process to compromise the `login` command.

Step 1: update the C compiler's code to detect `login.c` and insert a bug:

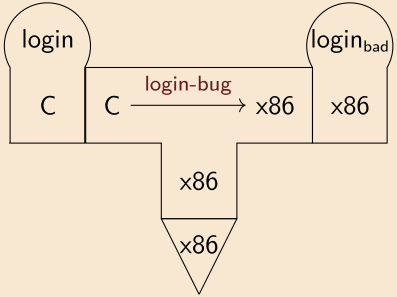
```
void compile(const char *program) {
  if (matches(program, "< login code >") {
     compile("< code for backdoor >");
  }
  ...
```

Compile and install the new C compiler:



Compromising `login`

Now the compiler will miscompile `login`:



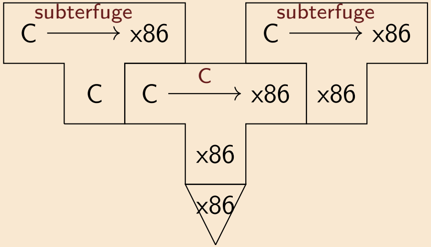
Problem: people will easily spot the bug in the compiler source.

The subterfuge

Step 2: update the C compiler code to detect `compiler.c` and insert a 2nd bug:

```
void compile(const char *program) {
  if (matches(program, "< login code >") {
     compile("< code for backdoor >");
  }
  if (matches(program, "< compiler code >") {
     compile("< code for miscompilation >");
  }
```

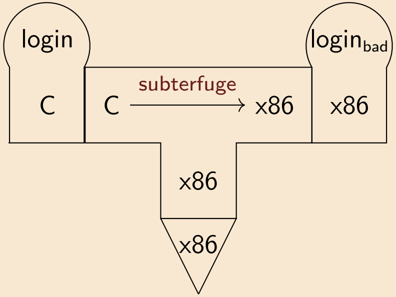
Compile and install the new C compiler:



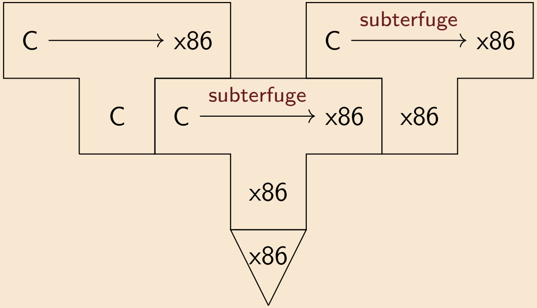
Finally: remove the bugs from the compiler source.

The compiler has learnt to insert backdoors

The compiler will still miscompile `login`:



The compiler will now also miscompile the compiler:



The system is **compromised**, with **no trace** in the `login` or compiler source.

We need to *debootstrap* to recover an uncompromised compiler.