Metaprogramming

These slides borrow heavily from Ben Wood's Fall '15 slides.

CS251 Programming Languages
Fall 2016, Lyn Turbak

Department of Computer Science
Wellesley College

How to implement a programming language

Interpretation

An **interpreter** written in the **implementation language** reads a program written in the **source language** and **evaluates** it.

Translation (a.k.a. compilation)

An **translator (**a.k.a. **compiler)** written in the **implementation language** reads a program written in the **source language** and **translates** it to an equivalent program in the **target language**.

But now we need implementations of:

implementation language

target language

How to implement a programming language

Can describe by deriving a "proof" of the implementation using these inference rules:

Interpreter Rule

$$\frac{\textbf{P-in-L program} \qquad \textbf{L interpreter machine}}{\textbf{P machine}}$$

Translator Rule

$$\frac{\textbf{P-in-S program} \qquad \textbf{S-to-T translator machine}}{\textbf{P-in-T program}}$$

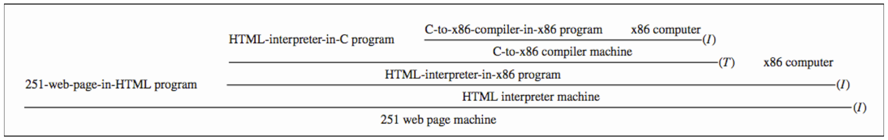
Implementation Derivation Example

Prove how to implement a "251 web page machine" using:

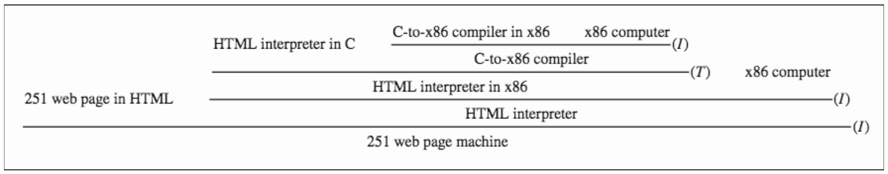
- 251-web-page-in-HTML program (a web page written in HTML)
- HTML-interpreter-in-C program (a web browser written in C)
- C-to-x86-translator-in-x86 program (a C compiler written in x86)
- x86 interpreter machine (an x86 computer)

No peaking ahead!

Implementation Derivation Example Solution



We can omit some occurrences of "program" and "machine":



Implementation Derivation Are Trees

And so we can represent them as nested structures, like nested bulleted lists:

- 251-web-page-in-HTML program
  - HTML-interpreter-in-C program
    - C-to-x86 compiler-in-x86 program
    - X86 computer
  - C-to-x86 compiler machine (I)
  - HTML-interpreter-in-x86 program (T)
  - x86 computer
- HTML interpreter machine (I)

251 web page machine (I)

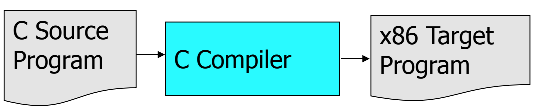
Version that shows conclusions below bullets. More similar to derivations with horizontal lines, but harder to create,and read

251 web page machine (I)

- 251-web-page-in-HTML program
- HTML interpreter machine (I)
  - HTML-interpreter-in-x86 program (T)
    - HTML-interpreter-in-C program
    - C-to-x86 compiler machine (I)
      - C-to-x86 compiler-in-x86 program
      - X86 computer
  - x86 computer

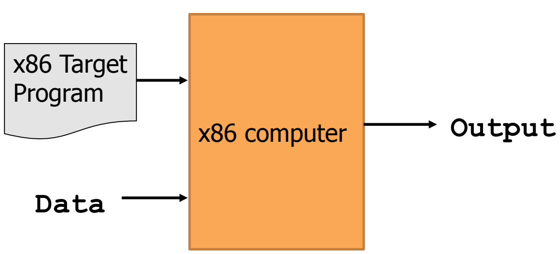
Preferred "top-down" version that shows conclusions above bullets.

Compiler

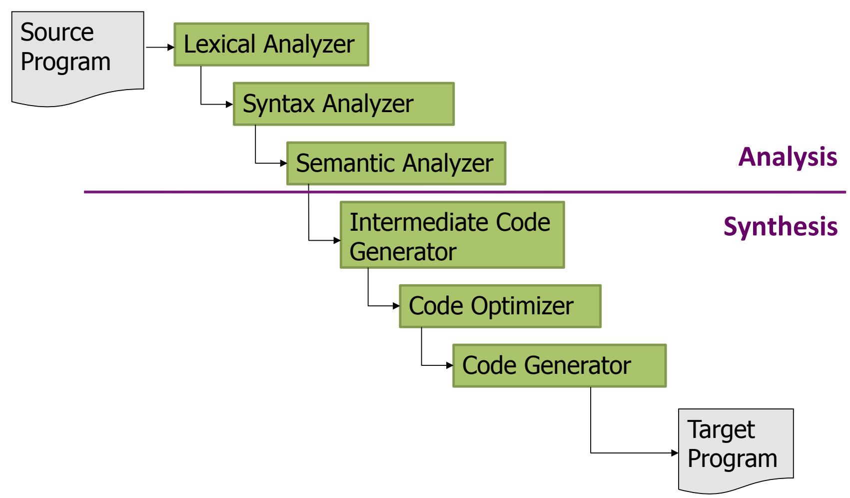



```
if (x == 0) {
  x = x + 1;
}
...
```

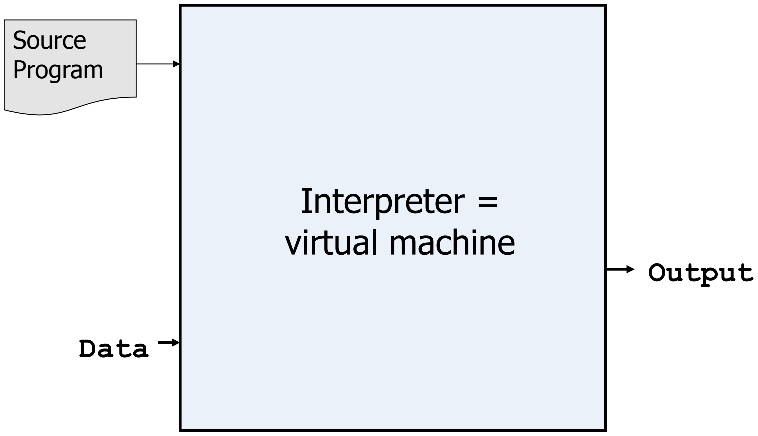
```
cmp (1000), $0
bne L
add (1000), $1
L:
...
```



Typical Compiler



Interpreters



Interpreters vs Compilers

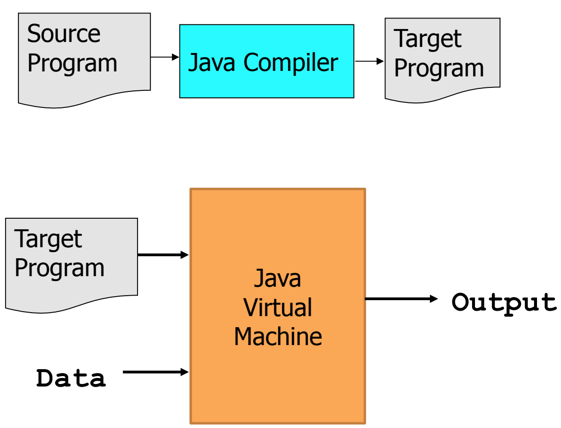
Interpreters

- No work ahead of time
- Incremental
- maybe inefficient

Compilers

- All work ahead of time
- See whole program (or more of program)
- Time and resources for analysis and optimization

Compilers... whose output is interpreted



Doesn't this look familiar?

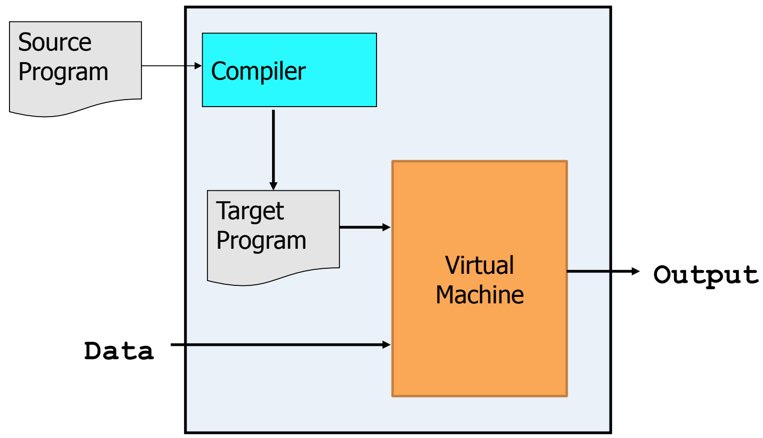
Java Compiler


```
if (x == 0) {
  x = x + 1;
}
...
```

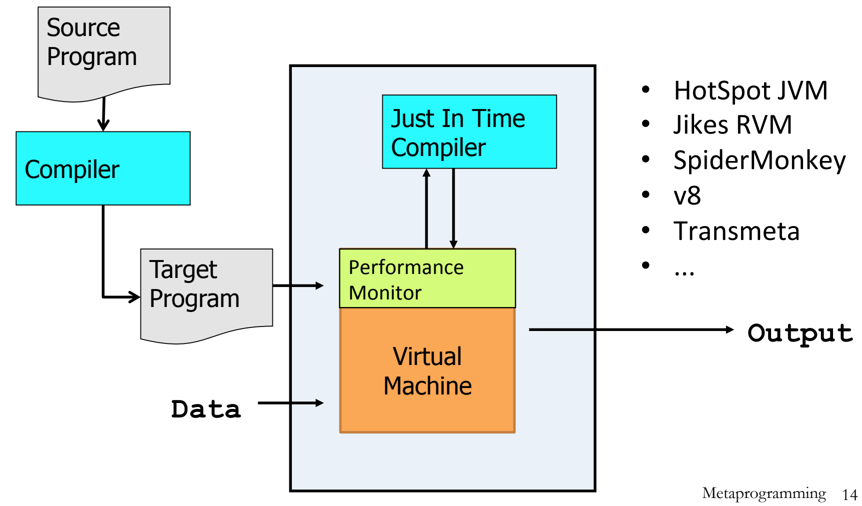
```
load 0
ifne L
load 0
inc
store 0
L:
...
```

(compare compiled C to compiled Java)

Interpreters... that use compilers.

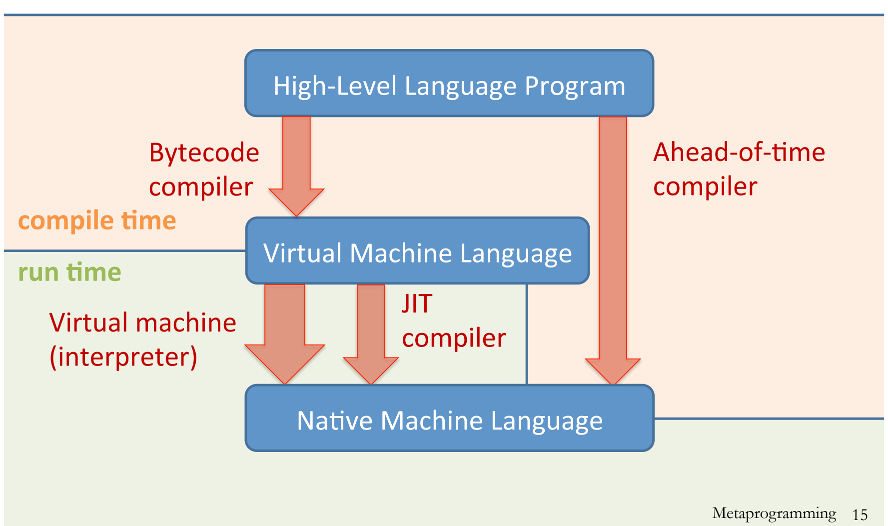


JIT Compilers and Optimization



- HotSpot JVM
- Jikes RVM
- SpiderMonkey
- v8
- Transmeta
- ...

Virtual Machine Model



Metacircularity and Bootstrapping

Many examples:

- Lisp in Lisp / Racket in Racket
- Python in Python: PyPy
- Java in Java: Jikes RVM, Maxine VM
- ...
- C-to-x86 compiler in C
- `eval` construct in languages like Lisp, JavaScript

How can this be possible?

Key insights to bootstrapping:

- The first implementation of a language **cannot** be in itself, but must be in some other language.
- Once you have one implementation of a language, you can implement it in itself.

Metacircularity Example 1: Problem

Suppose you are given:

- Racket-interpreter-in-SML program
- SML machine
- Racket-interpreter-in-Racket program

How do you create a Racket interpreter machine using the Racket-interpreter-in-Racket program?

Metacircularity Example 1: Solution

Suppose you are given:

- Racket-interpreter-in-SML program
- SML machine
- Racket-interpreter-in-Racket program

How do you create a Racket interpreter machine using the Racket-interpreter-in-Racket program?

Racket interpreter machine #2 (I)
❑ Racket-interpreter-in-Racket program
❑ Racket-interpreter machine #1 (I)
    ✧ Racket-interpreter-in-SML program
    ✧ SML machine

But why create Racket interpreter machine #2 when you already have Racket-interpreter machine #1?

Metacircularity Example 1: More Realistic

Suppose you are given:

- Racket-subset-interpreter-in-SML program (implements only core Racket features; no desugaring or other frills)
- SML machine
- Full-Racket-interpreter-in-Racket program

How do you create a Full-Racket interpreter machine using the Full-Racket-interpreter-in-Racket program?

Full-Racket interpreter machine (I)
❑ Racket-interpreter-in-Racket program
❑ Racket-subset interpreter machine #1 (I)
    ✧ Racket-subset-interpreter-in-SML program
    ✧ SML machine

Metacircularity Example 2: Problem

Suppose you are given:

- C-to-x86-translator-in-x86 program (a C compiler written in x86)
- x86 interpreter machine (an x86 computer)
- C-to-x86-translator-in-C-subset program

How do you compile the C-to-x86-translator-in-C ?

Metacircularity Example 2: Solution

Suppose you are given:

- C-to-x86-translator-in-x86 program (a C compiler written in x86)
- x86 interpreter machine (an x86 computer)
- C-to-x86-translator-in-C program

How do you compile the C-to-x86-translator-in-C ?

C-to-x86-translator machine #2 (I)
- ❑ C-to-x86-translator-in-x86 program #2 (T)
  - ✧ C-to-x86-translator-in-C
  - ✧ C-to-x86-translator machine #1 (I)
    - ○ C-to-x86-translator-in-x86 program #1
    - ○ x86 computer
- ❑ x86 computer

But why create C-to-x86-translator-in-x86 program #2 (T)
when you already have C-to-x86-translator-in-x86 program #1?

Metacircularity Example 2: More Realistic

Suppose you are given:

- C-subset-to-x86-translator-in-x86 program
 (a compiler for a subset of C written in x86)
- x86 interpreter machine (an x86 computer)
- Full-C-to-x86-translator-in-C-subset program
 (a compiler for the full C language written in a subset of C)

How do you create a Full-C-to-x86-translator machine ?

Full-C-to-x86-translator machine (I)
- ❑ Full-C-to-x86-translator-in-x86 program (T)
  - ✧ Full-C-to-x86-translator-in-C-subset
  - ✧ C-subset-to-x86-translator machine (I)
    - ○ C-subset-to-x86-translator-in-x86 program
    - ○ x86 computer
- ❑ x86 computer

A long line of C compilers

C-version_n-to-target_n-translator machine (I)
- ❑ C-version_n-to-target_n-translator program in target_n-1 (T)
  - ✧ C-version_n-to-target_n-translator program in C-version_n-1
  - ✧ C-version_n-1-to-target_n-1 translator machine (I)
    - ○ C-version_n-1-to-target_n_1-translator program in target_n-2 (T)

      ⋮
      - ➢ C-version_2-to-target_2-translator-program in target_1 (T)
        - ▪ C-version_2-to-target_2-translator program in C-version_1
        - ▪ C-version_1-to-target_1 translator (I)
          - • C-version_1-to-target_1-translator program in assembly_0
          - • assembly_0 computer
      - ➢ target_1 computer

      ⋮
    - ○ target_n-2 computer
- ❑ target_n-1 computer

- ○ The versions of C and target languages can change at each stage.
- ○ Trojan horses from earlier source files can remain in translator machines even if they're not in later source file! See Ken Thompson's *Reflection on Trusting Trust*

Remember: language != implementation

- Easy to confuse "the way this language is usually implemented" or "the implementation I use" with "the language itself."
- Java and Racket can be compiled to x86
- C can be interpreted in Racket
- x86 can be compiled to JavaScript
- Can we compile C/C++ to Javascript?
 http://kripken.github.io/emscripten-site/

More Metaprogramming in SML

- We've already seen PostFix in SML
- A sequences of expression languages implemented in SML that look closer and closer to Racket:
  - Intex (Today & Tue Dec. 6)
    - Interpret Intex in SML
    - Compile Intex to Postfix
  - Bindex (Tue/Wed. Dec. 6/7)
  - Valex (won't cover this semester)
  - HOFL (higher-order functional language; won't cover this semester).