# COMP 520 - Compilers

## Lecture 19 – April 26, 2022

*Compiler Bootstrapping*

# Announcements

- PA5 – final checkpoint
  - submission directory will close Wed May 27 at midnight
  - submission instructions are identical to PA4, plus
    - upload guide to your compiler (see assignment)
    - if you have implemented extra credit, include a Tests directory
  - readiness tester: /check/pa4.pl (i.e. same as pa4)

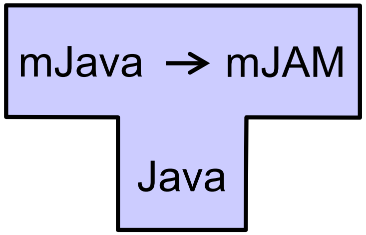
- Final exam
  - Thu May 5, Noon – 3PM
    - exam is intended to take 2 hours, but you have 3 hours to complete it
    - comprehensive with emphasis on the second half of the class
    - midterm and final have equal weight
  - rules
    - Open book, open notes
      - No general search or outside help
      - You have to sign the pledge

# Topics today

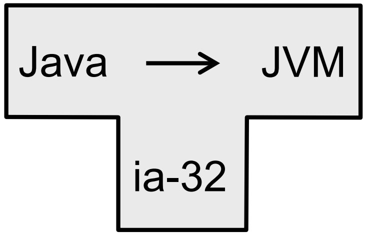
- Compilers, Interpreters, and Bootstrapping
  - material from Chapter 2 in our text
  - this material will not be on the exam

# Compilers and Interpreters: diagrams

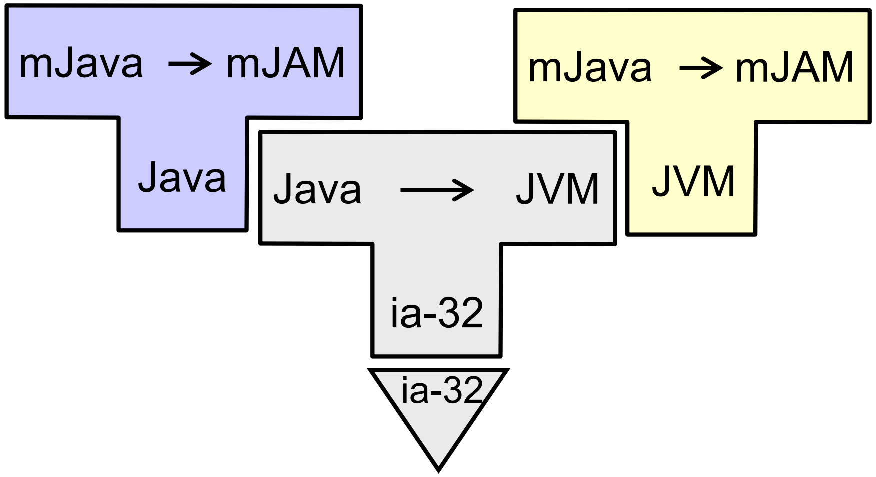
- your miniJava compiler




- javac compiler on ia-32 machine

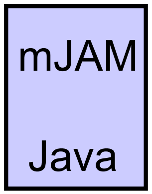



- Compiling the miniJava compiler using javac on ia-32

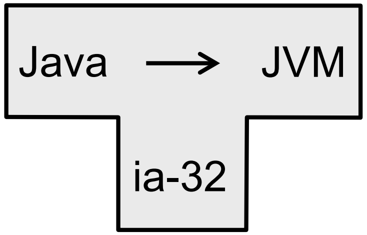


# Compiling the mJAM interpreter

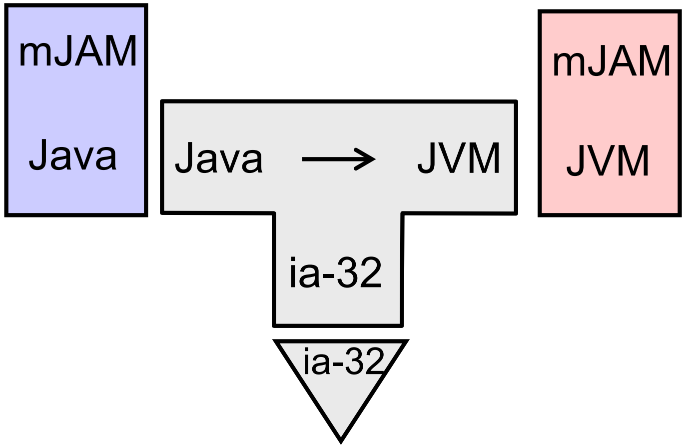
- mJAM interpreter




- javac compiler on ia-32

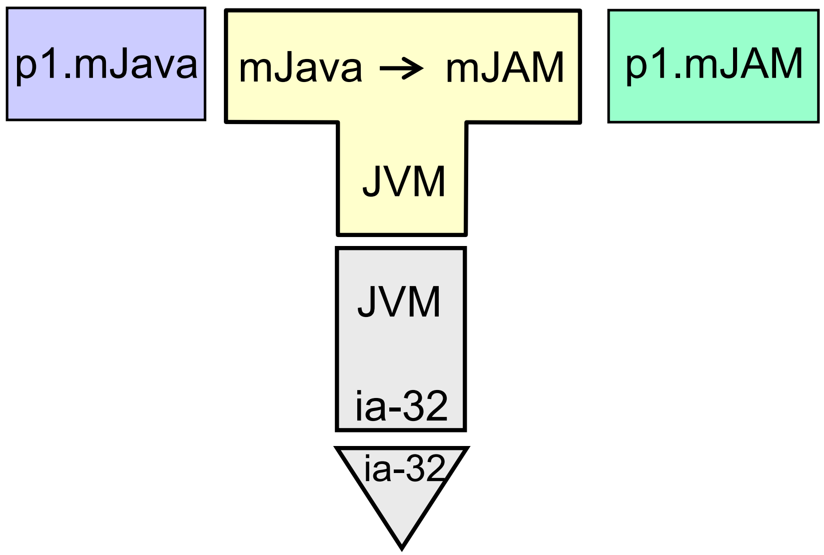



- Compiling the TAM interpreter using javac on ia-32

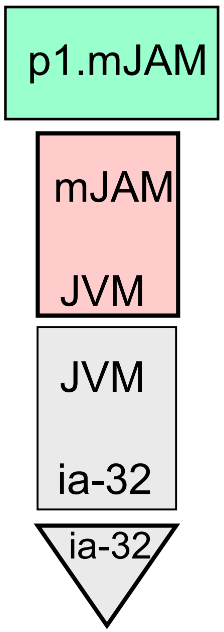


# The miniJava compiler in action

- Compiling a miniJava program p1.mJava on ia-32

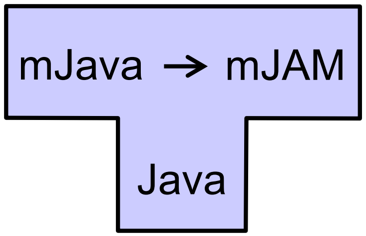



- Executing the compiled program on ia-32



# Compiler implementation language

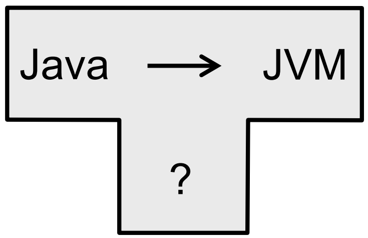
- The miniJava compiler is implemented in Java



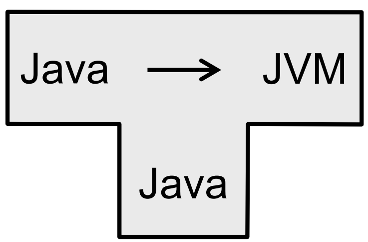

- Why?
  - Java is a high-level language
    - can express key features of a compiler
      - sophisticated modularization
      - advanced data structures
      - design patterns
  - Java is portable
    - can develop a miniJava compiler under Windows or Linux and run on either

# Compiler implementation language

- What is the implementation language of Oracle's Java compiler?



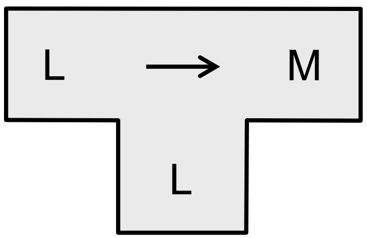

- Like us, the authors of the (Sun) Java compiler also prefer to implement the compiler in Java!



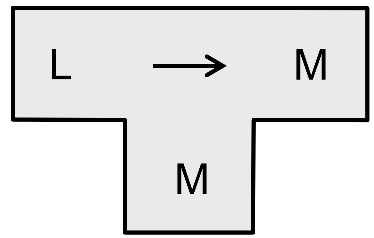

- A compiler for language L written in L is called a portable compiler
  - How do we compile such a compiler?

# Compiler bootstrapping

- Given a pair of compilers from (high-level) language L into (machine) language M




portable compiler




native compiler

we can conveniently

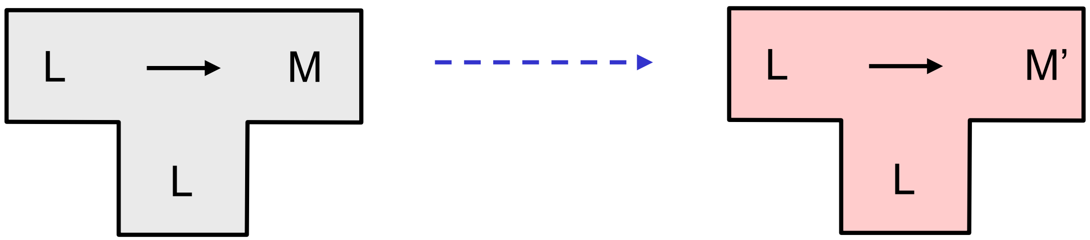
- retarget: a compiler for L generating code for a different machine M'
- extend: a compiler for L', an extension of language L
- improve: a better (e.g. more optimized) compiler for L into M

using a technique called compiler bootstrapping

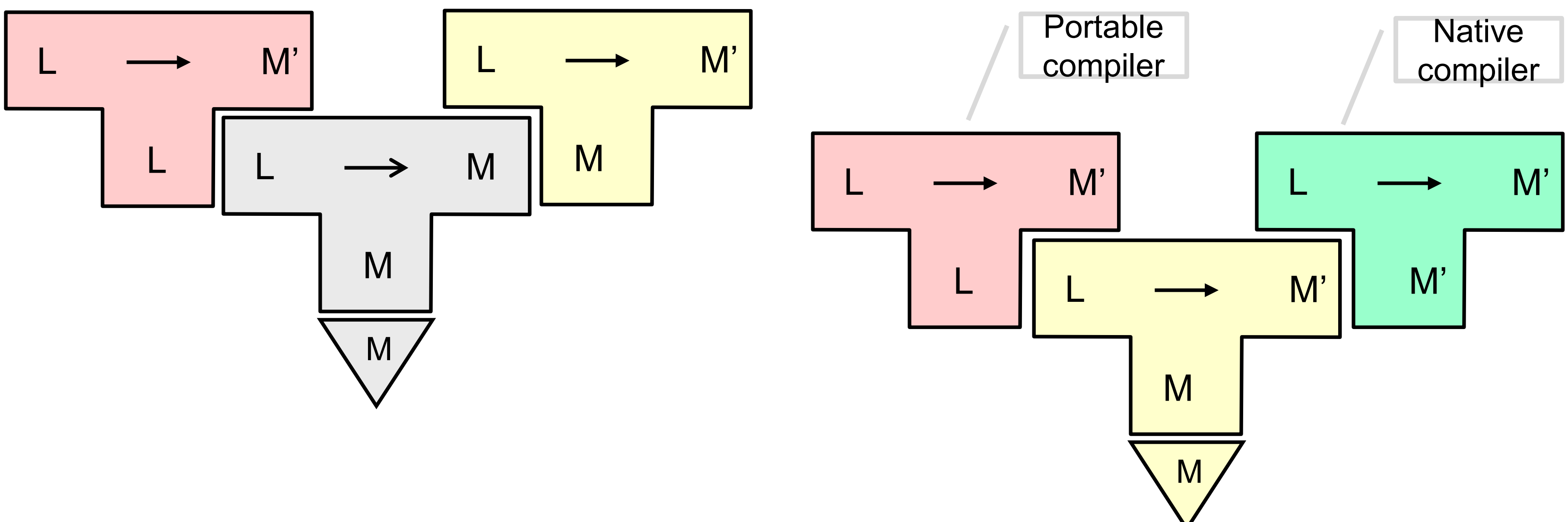
- which yields a new pair of (portable, native) compilers

# Retargeting a compiler

1. Write a new code generator to retarget the portable compiler to M’

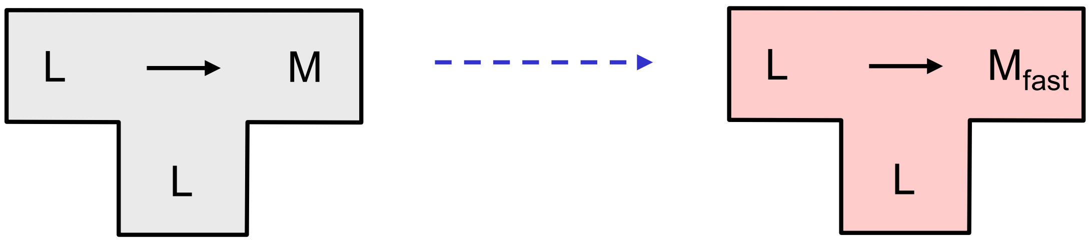



2. Two-step bootstrap to construct the native compiler

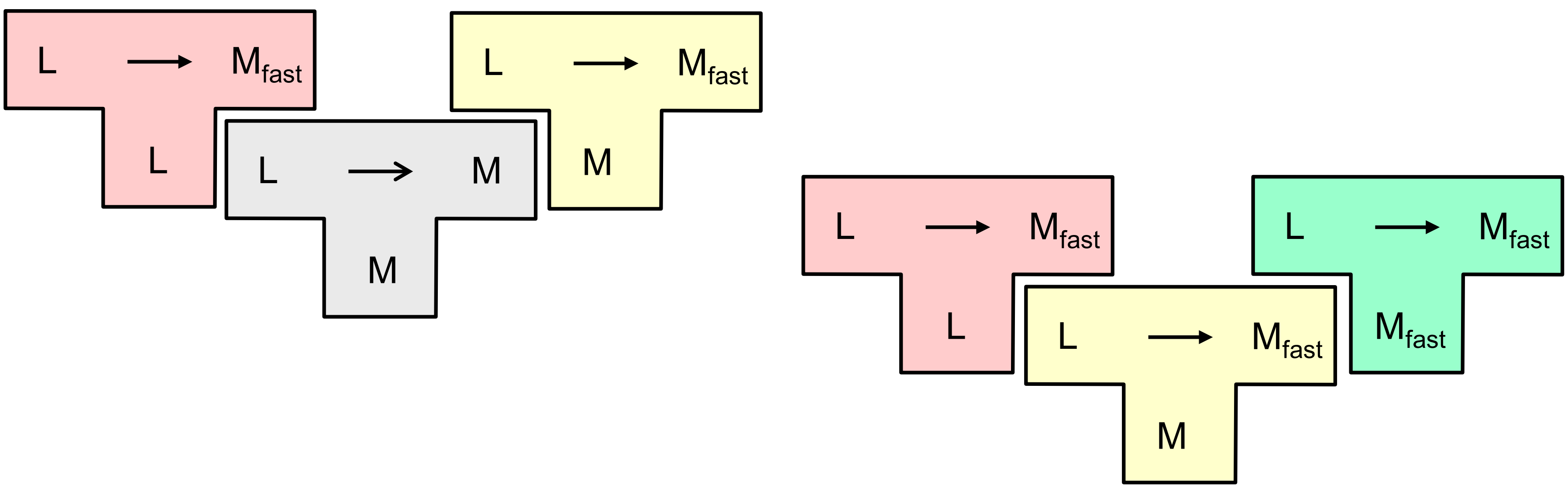


# Improving a compiler

1. Incorporate optimizations into the portable compiler

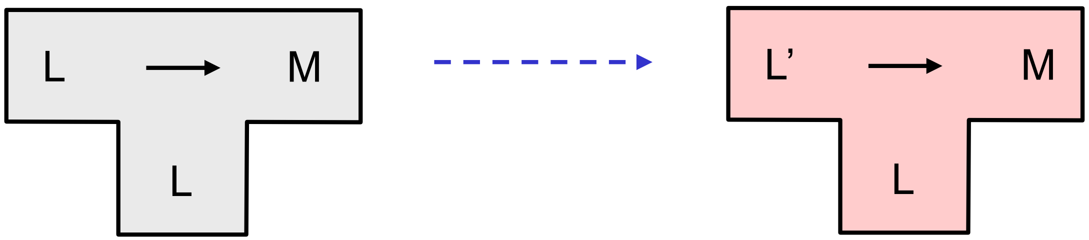



2. Two-step bootstrap to create (optimized) native compiler

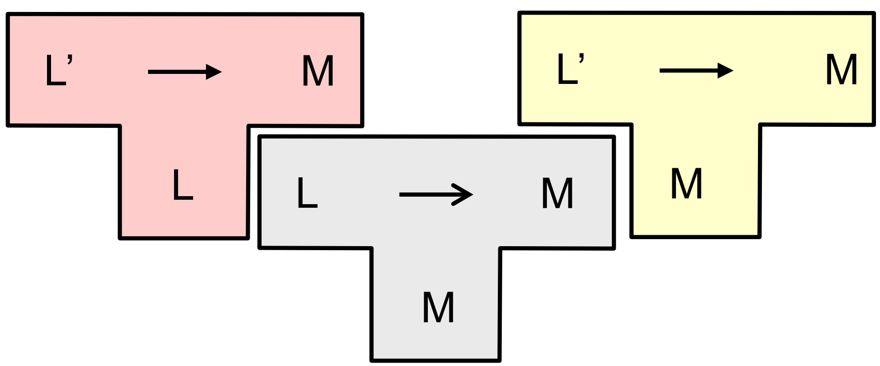


# Extending the source language (1)

1. Extend the compiler to handle new features of source language L’ $\supseteq$ L
   - but stick to features of L in the *implementation*



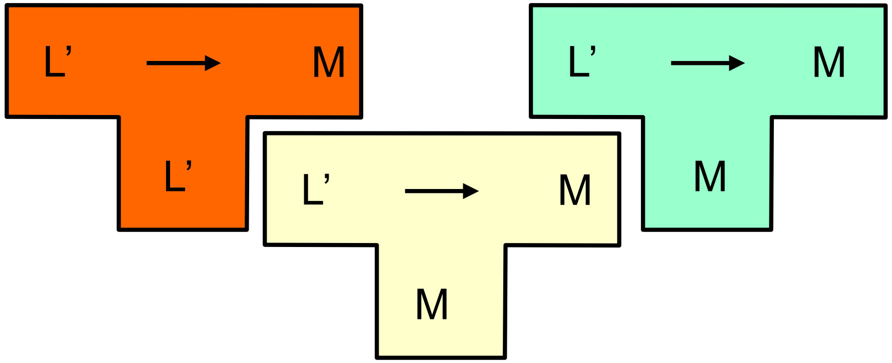

2. Bootstrap (first half)



# Extending the source language (2)

3. Rewrite the new compiler using the extended features of L’

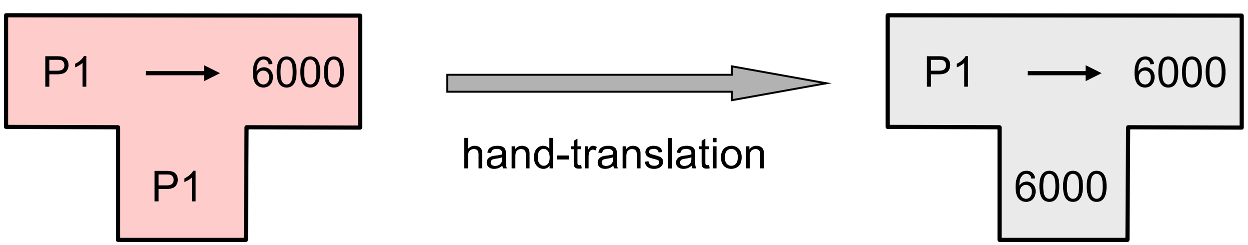

4. Bootstrap (second half)



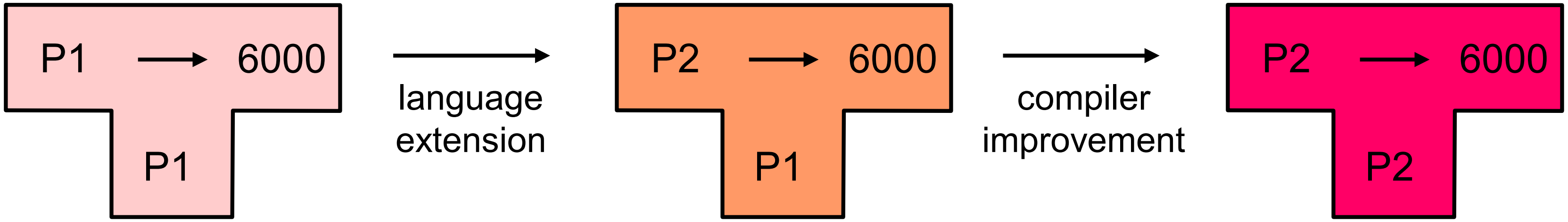
# How to construct the first portable compiler?

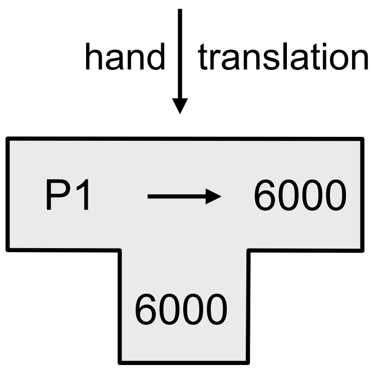
- Incrementally, using repeated language extensions!

- Example:  the first Pascal compiler
  - ETH Zurich, circa 1970
  - Machine: CDC 6000
  - Available languages: Scallop (CDC Assembler), Fortran
    - Initial attempt to write Pascal compiler using Fortran was a failure, and was discarded
  - A very simple and small compiler was written in a highly incomplete version of Pascal (P1)
    - It was translated by hand (!) to CDC Assembler
  - Thus started the bootstrap cycle!

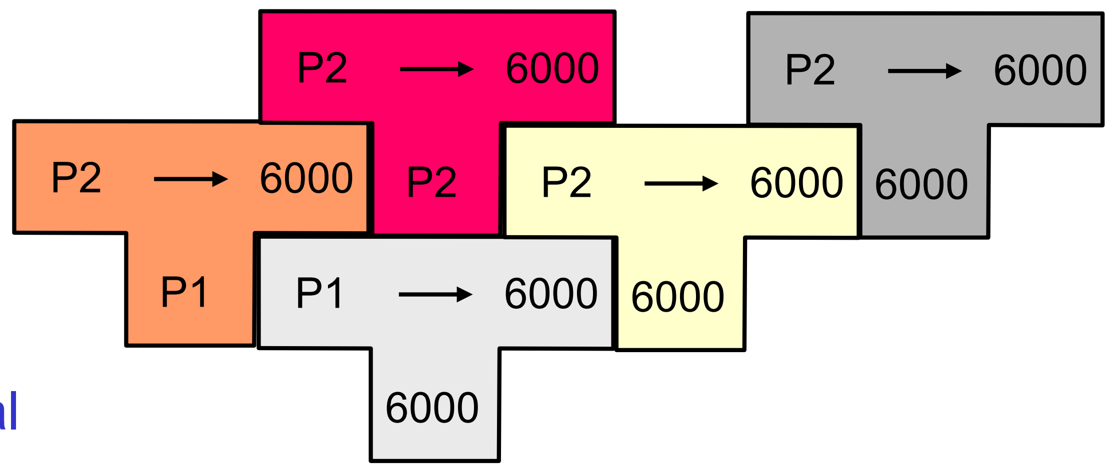


# The First Pascal Compiler




Two-step bootstrap




P1 = incomplete Pascal
P2 = full Pascal

# The Java compiler

- So is our javac the *native* compiler for ia-32 (or x86-64) ?
  - Well, actually not
  - it's actually more like a pre-jitted set of JVM classes for the *portable* compiler
  - but the compiler does use language improvement bootstrapping to make use of new language features

- JVM is a C++ program
  - it leverages the C++ compilers to generate a high quality interpreter on each architecture
  - and performs JIT compilation
  - it also provides native code for a boatload of basic library capabilities
    - e.g. GUIs, graphics

# Language extension: example

- We have a compiler $C_1$ for a subset of C
  - handles escape sequences '\\' and '\n' in character literals
  - produces MIPS assembly code

- We want to extend the subset of C
  - allow the escape sequence '\t' (horizontal tab, ASCII code 0x09) to appear in character literals

- Relevant routine is `convert()`, in LexicalAnalysis section of $C_1$
  - converts character escape sequences in char literals to ascii codes

# procedure convert()

```
int convert() {
    int c = nextchar();
    if (c != '\\')
        return c;
    c = nextchar();
    if (c == '\\')
        return '\\';
    if (c == 'n')
        return '\n';
    error();
}
```

code in $C_1$ compiler written in $C_1$ subset

```
convert:
    subu  sp, sp, 24
    sw    ra, 16(sp)
    jal   nextchar      ; $2 result
    li    $3, 0x5c      ; backslash
    bne   $2, $3, $L1
    jal   nextchar      ; $2 result
    move  $3, $2
    li    $2, 0x5c      ; backslash
    beq   $3, $2, $L1
    li    $4, 0x6e      ; 'n'
    li    $2, 0x0a      ; '\n'
    beq   $3, $4, $L1
    jal   error
$L1:
    lw    ra, 16(sp)    ; return
    addu  sp, sp, 24    ; result in $2
    j     ra
```

$C_1$ compiled code for convert()

# Extending $C_1$

- First try

```
int convert() {
    int c = nextchar();
    if (c != '\\')
        return c;
    c = nextchar();
    if (c == '\\')
        return '\\';
    if (c == 'n')
        return '\n';
    if (c == 't')
        return '\t';
    error();
}
```

Generates a compile time error

Where?

# Extending $C_1$

- Second try

```
int convert() {
    int c = nextchar();
    if (c != '\\')
        return c;
    c = nextchar();
    if (c == '\\')
        return '\\';
    if (c == 'n')
        return '\n';
    if (c == 't')
        return 0x09;
    error();
}
```

- The $C_1$ compiler handles this just fine
  - $C_1$ compiles the extended compiler
  - produces a compiler $C_2$ that accepts '\t' in char literals

```
convert:
        subu  sp, sp, 24
        sw    ra, 16(sp)
        jal   nextchar       ; $2 result
        li    $3, 0x5c       ; backslash
        bne   $2, $3, $L1
        jal   nextchar       ; $2 result
        move  $3, $2
        li    $2, 0x5c       ; backslash
        beq   $3, $2, $L1
        li    $4, 0x6e       ; 'n'
        li    $2, 0x0a       ; '\n'
        beq   $3, $4, $L1
        li    $4, 0x74       ; 't'
        li    $2, 0x09       ; 0x09
        beq   $3, $4, $L1
        jal   error
$L1:
        lw    ra, 16(sp)     ; return
        addu  sp, sp, 24     ; result in $2
        j     ra
```

# Completing the bootstrap

- $C_2$ will now be able to compile the preferred version of convert()
  - generates a third compiler $C_3$
  - now discard C1, C2 and retain the clean version of convert() in $C_3$

```
int convert() {
    int c = nextchar();
    if (c != ‘\\’)
        return c;
    c = nextchar();
    if (c == ‘\\’)
        return ‘\\’;
    if (c == ‘n’)
        return ‘\n’;
    if (c == ‘t’)
        return ‘\t’;
    error();
}
```

# So what happened?

- Some knowledge was "baked into" the (portable, native) compiler pair
  - The relationship between '\t' and its character code 0x09 is no longer visible in the portable compiler
  - Yet the native compiler somehow reproduces it

- Is this OK?
  - It's great for compiler development
  - It's not ok for computer security!
    - The compiler can contain an embedded virus that propagates itself to future compilers
      - not visible in the portable compiler
      - but propagated into binaries
      - and into binaries of detectors!
    - "Reflections on trusting trust" – Ken Thompson 1984

# Generating a compiler from an interpreter

- Partial evaluator
  - a kind of JIT compiler, but highly optimizing
    - Suppose we have prog(x,y), partial evaluator PE and known input x
    - (PE prog x) is a *residual program* such that
    - (PE prog x)(y) = prog(x,y)
      - The partial evaluator "specializes" prog for known input x

- Bootstrapping a partial evaluator: the "Futamura projections"
  - First projection: *compiles* a program P in language L given an interpreter for L
    - $(PE_L \ interpreter_L \ P_L)(x) = P_L \ (x)$
  - Second projection: builds a *compiler* given an interpreter
    - $(PE_L \ \ PE_L \ \ interpreter_L)(P_L) \ (x) = (PE_L \ interpreter_L \ P_L) \ (x)$
  - Third projection: builds a *compiler generator* ☺
    - $(PE_L \ \ PE_L \ \ PE_L) \ (interpreter_L) = (PE_L \ \ PE_L \ \ Interpreter_L)$

# Back to something real …

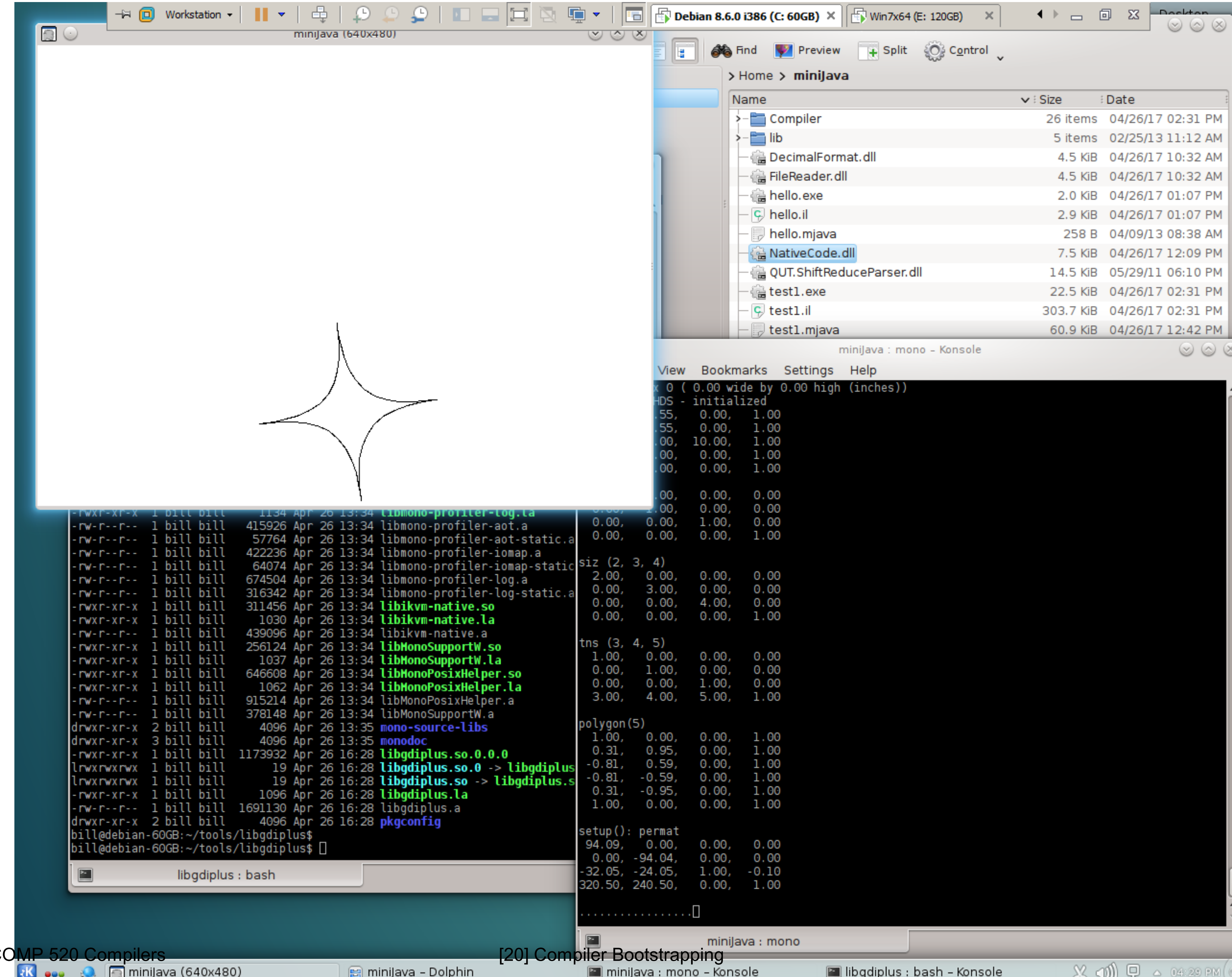
- miniJava compiler
  - Built a few years ago by Bill Lewis
  - miniJava plus multidimensional arrays and floating point arithmetic and lots of other features
    - also able to link to an external libraries
  - targeted to .NET (Microsoft’s virtual machine)

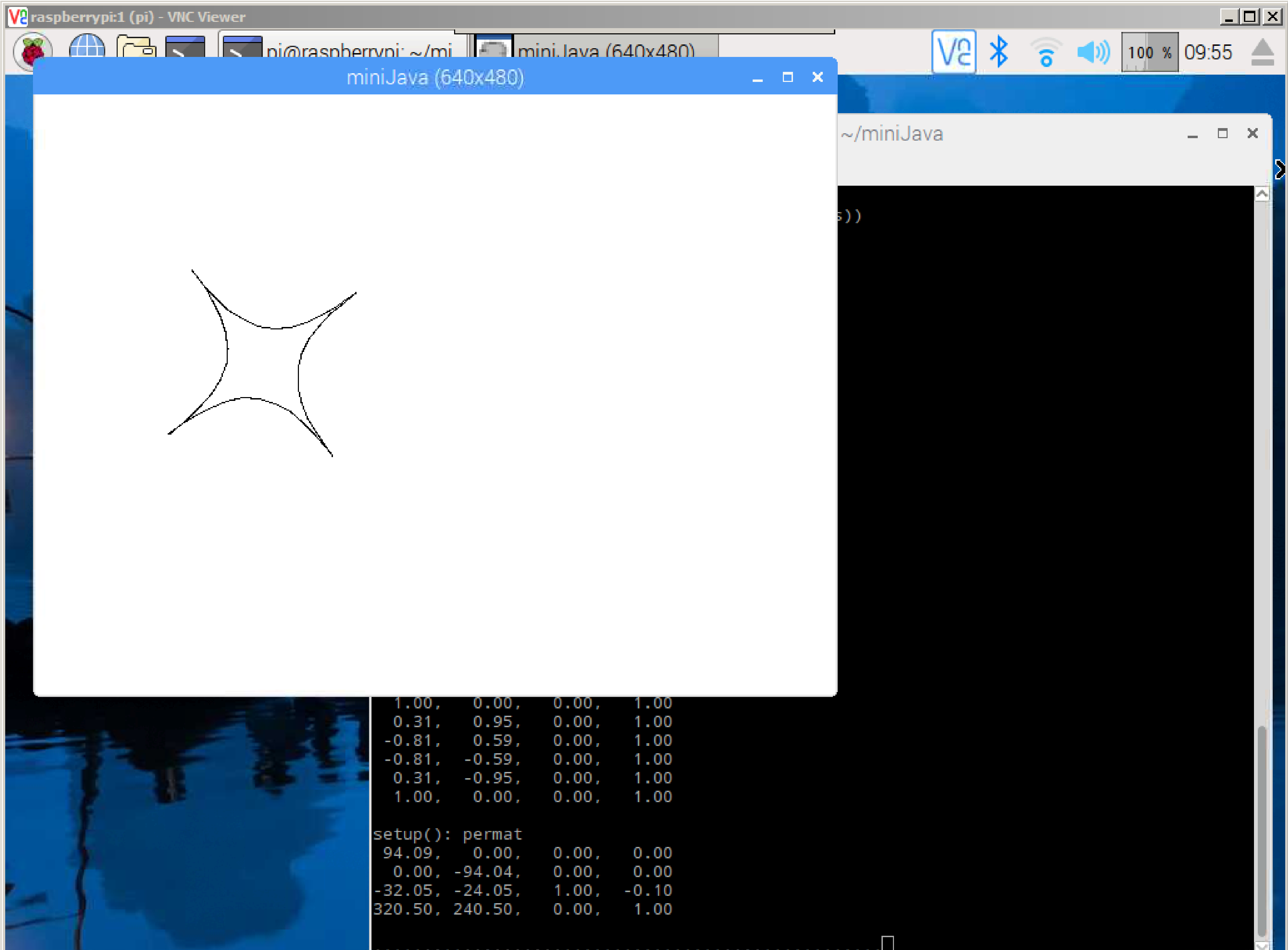
(1) Question about open source implementation of .NET (mono) ?

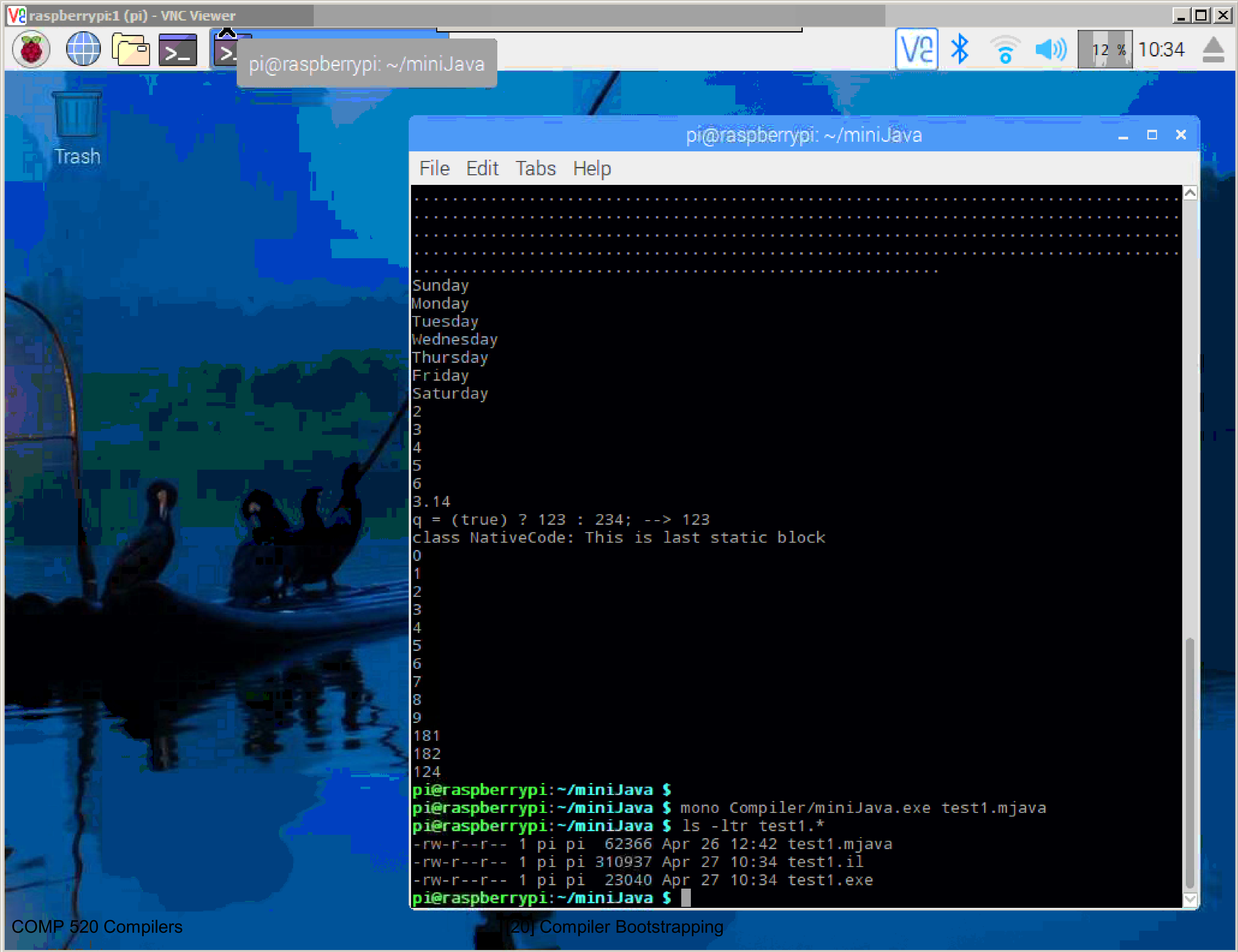
- Answered by dusting off the miniJava compiler
- and substituting mono for .NET
- It runs!

(2) Portability of the mono environment ?

- Recompiled the mono environment for a Raspberry Pi Zero ($5)
- It runs!


Workstation
Debian 8.6.0 i386 (C: 60GB)
Win7x64 (E: 120GB)
miniJava (640x480)
Find
Preview
Split
Control
Home > miniJava
Name
Size
Date
Compiler 26 items 04/26/17 02:31 PM
lib 5 items 02/25/13 11:12 AM
DecimalFormat.dll 4.5 KiB 04/26/17 10:32 AM
FileReader.dll 4.5 KiB 04/26/17 10:32 AM
hello.exe 2.0 KiB 04/26/17 01:07 PM
hello.il 2.9 KiB 04/26/17 01:07 PM
hello.mjava 258 B 04/09/13 08:38 AM
NativeCode.dll 7.5 KiB 04/26/17 12:09 PM
QUT.ShiftReduceParser.dll 14.5 KiB 05/29/11 06:10 PM
test1.exe 22.5 KiB 04/26/17 02:31 PM
test1.il 303.7 KiB 04/26/17 02:31 PM
test1.mjava 60.9 KiB 04/26/17 12:42 PM
miniJava : mono – Konsole
View
Bookmarks
Settings
Help
x 0 ( 0.00 wide by 0.00 high (inches))
HDS - initialized
siz (2, 3, 4)
tns (3, 4, 5)
polygon(5)
setup(): permat
-rw-r--r-- 1 bill bill 415926 Apr 26 13:34 libmono-profiler-aot.a
-rw-r--r-- 1 bill bill 57764 Apr 26 13:34 libmono-profiler-aot-static.a
-rw-r--r-- 1 bill bill 422236 Apr 26 13:34 libmono-profiler-iomap.a
-rw-r--r-- 1 bill bill 64074 Apr 26 13:34 libmono-profiler-iomap-static
-rw-r--r-- 1 bill bill 674504 Apr 26 13:34 libmono-profiler-log.a
-rw-r--r-- 1 bill bill 316342 Apr 26 13:34 libmono-profiler-log-static.a
-rwxr-xr-x 1 bill bill 311456 Apr 26 13:34 libikvm-native.so
-rwxr-xr-x 1 bill bill 1030 Apr 26 13:34 libikvm-native.la
-rw-r--r-- 1 bill bill 439096 Apr 26 13:34 libikvm-native.a
-rwxr-xr-x 1 bill bill 256124 Apr 26 13:34 libMonoSupportW.so
-rwxr-xr-x 1 bill bill 1037 Apr 26 13:34 libMonoSupportW.la
-rwxr-xr-x 1 bill bill 646608 Apr 26 13:34 libMonoPosixHelper.so
-rwxr-xr-x 1 bill bill 1062 Apr 26 13:34 libMonoPosixHelper.la
-rw-r--r-- 1 bill bill 915214 Apr 26 13:34 libMonoPosixHelper.a
-rw-r--r-- 1 bill bill 378148 Apr 26 13:34 libMonoSupportW.a
drwxr-xr-x 2 bill bill 4096 Apr 26 13:35 mono-source-libs
drwxr-xr-x 3 bill bill 4096 Apr 26 13:35 monodoc
-rwxr-xr-x 1 bill bill 1173932 Apr 26 16:28 libgdiplus.so.0.0.0
lrwxrwxrwx 1 bill bill 19 Apr 26 16:28 libgdiplus.so.0 -> libgdiplus
lrwxrwxrwx 1 bill bill 19 Apr 26 16:28 libgdiplus.so -> libgdiplus.s
-rwxr-xr-x 1 bill bill 1096 Apr 26 16:28 libgdiplus.la
-rw-r--r-- 1 bill bill 1691130 Apr 26 16:28 libgdiplus.a
drwxr-xr-x 2 bill bill 4096 Apr 26 16:28 pkgconfig
bill@debian-60GB:~/tools/libgdiplus$
bill@debian-60GB:~/tools/libgdiplus$
libgdiplus : bash
miniJava : mono
miniJava (640x480)
miniJava – Dolphin
miniJava : mono – Konsole
libgdiplus : bash – Konsole


raspberrypi:1 (pi) - VNC Viewer
pi@raspberrypi: ~/mi
miniJava (640x480)
100 %
09:55
miniJava (640x480)
~/miniJava
s))
1.00, 0.00, 0.00, 1.00
0.31, 0.95, 0.00, 1.00
-0.81, 0.59, 0.00, 1.00
-0.81, -0.59, 0.00, 1.00
0.31, -0.95, 0.00, 1.00
1.00, 0.00, 0.00, 1.00
setup(): permat
94.09, 0.00, 0.00, 0.00
0.00, -94.04, 0.00, 0.00
-32.05, -24.05, 1.00, -0.10
320.50, 240.50, 0.00, 1.00


raspberrypi:1 (pi) - VNC Viewer
pi@raspberrypi: ~/miniJava
10:34
Trash
pi@raspberrypi: ~/miniJava
File Edit Tabs Help
Sunday
Monday
Tuesday
Wednesday
Thursday
Friday
Saturday
2
3
4
5
6
3.14
q = (true) ? 123 : 234; --> 123
class NativeCode: This is last static block
0
1
2
3
4
5
6
7
8
9
181
182
124
pi@raspberrypi:~/miniJava $
pi@raspberrypi:~/miniJava $ mono Compiler/miniJava.exe test1.mjava
pi@raspberrypi:~/miniJava $ ls -ltr test1.*
-rw-r--r-- 1 pi pi  62366 Apr 26 12:42 test1.mjava
-rw-r--r-- 1 pi pi 310937 Apr 27 10:34 test1.il
-rw-r--r-- 1 pi pi  23040 Apr 27 10:34 test1.exe
pi@raspberrypi:~/miniJava $

# Wrap-up

- Compilers and interpreters
  - Critical components in modern programming
    - Portability, IDEs, version control, configuration management, etc.
    - Their construction draws on all parts of CS
    - algorithms, data structures, automata theory, programming languages, graph theory, and software engineering

- (Much) we didn't cover
  - error recovery
    - in the scanner and parser
  - optimization
    - loops and arrays, compiling for the memory hierarchy
  - complex programming language features
    - separate compilation (imports / exports / packages)
    - overloading and overriding
    - interfaces, generics, nested classes
    - concurrency

# Course evaluation

- Please provide some feedback on this course
  - This has not been my best semester ☹
  - I hope you were nevertheless gain some insight and interest in compilers and compilation

- Course evaluation mechanism
  - online through Connect Carolina
  - closes at midnight tomorrow night!

- Compilers
  - compilers are one of the key tools enabling computer science
  - you might not ever write another compiler, but you'll know how they work and you'll be less daunted by errors from a compiler
  - there's much more to compilers than we've covered!