Introduction to Compilation, Just-in-Time Compilers and Virtual Machines

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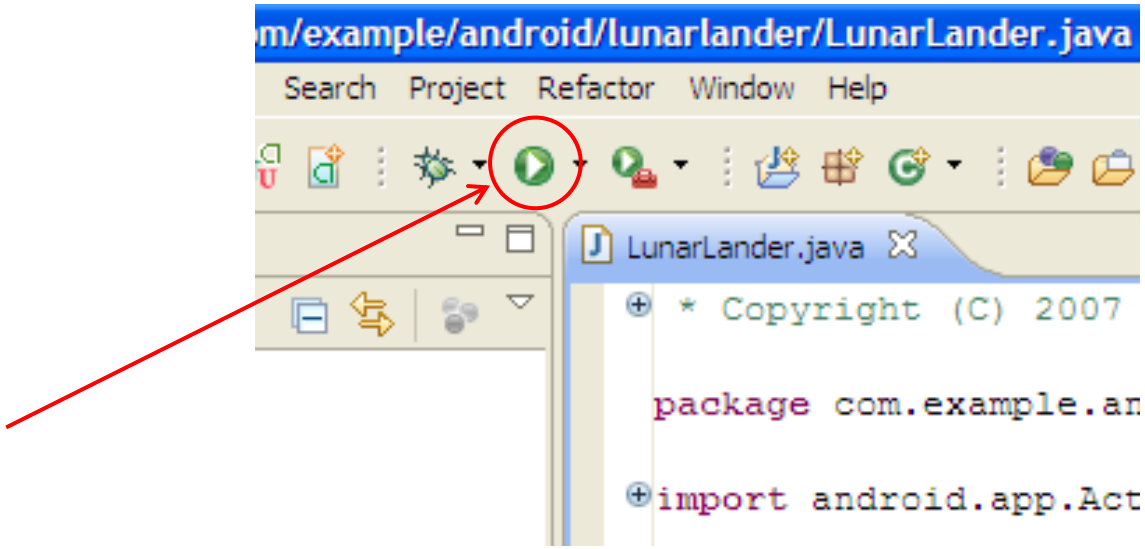
ALF Project

About this Talk



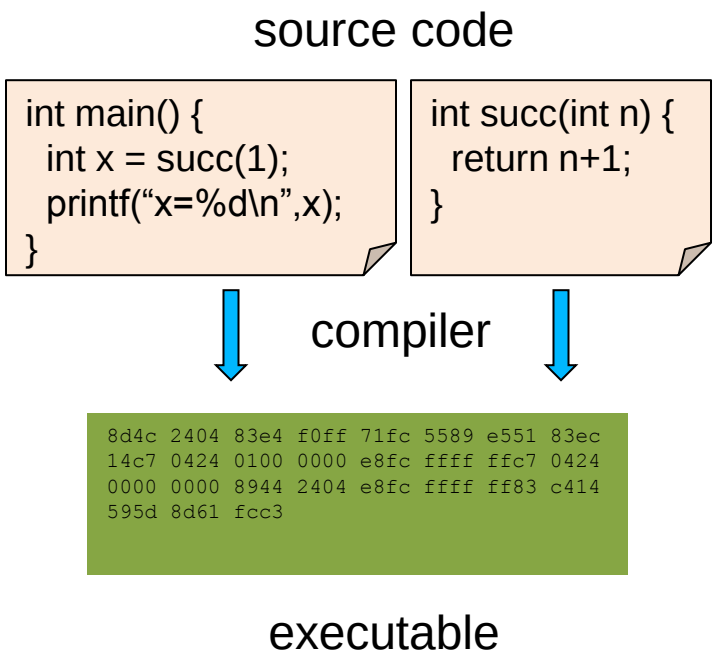
- This is an introduction
- Please, ask questions whenever unclear

Agenda

- Static Compilation
  - binutils
  - compilers
- Virtualization
- JIT Compilers
  - garbage collection
  - profiling

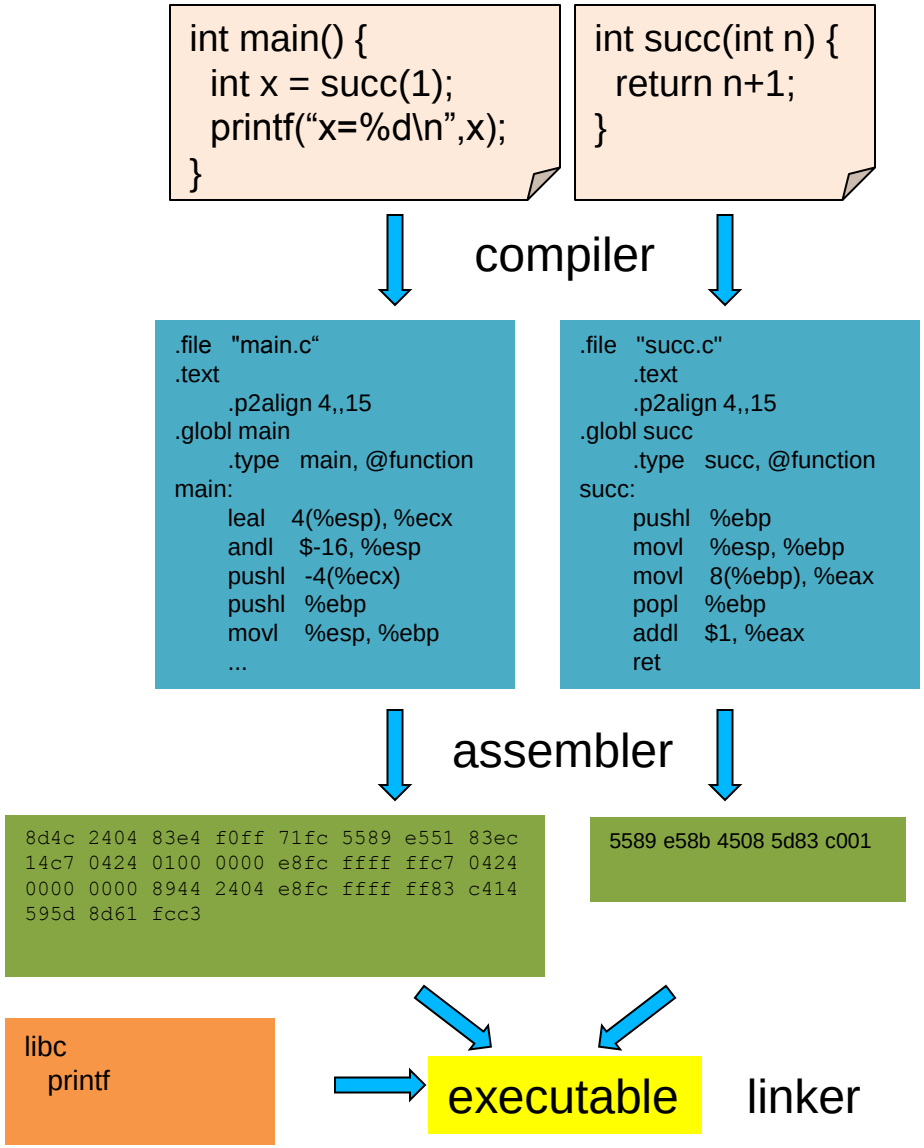
Static Compilation

- Translate from high-level programming language to machine code
- In addition
  - optimization
  - separate compilation
  - packaging: libraries
  - debug, profiling...
- Examples in C

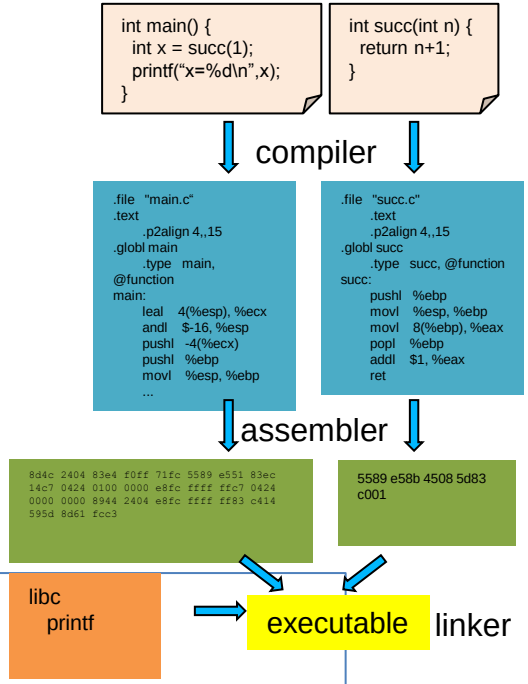


In More Details

- Precisely:
  - the *compiler* translates source to assembly
  - users invoke the *driver*
  - the *binutils* (binary utilities) deal with the rest
  - the driver invokes the tools as necessary



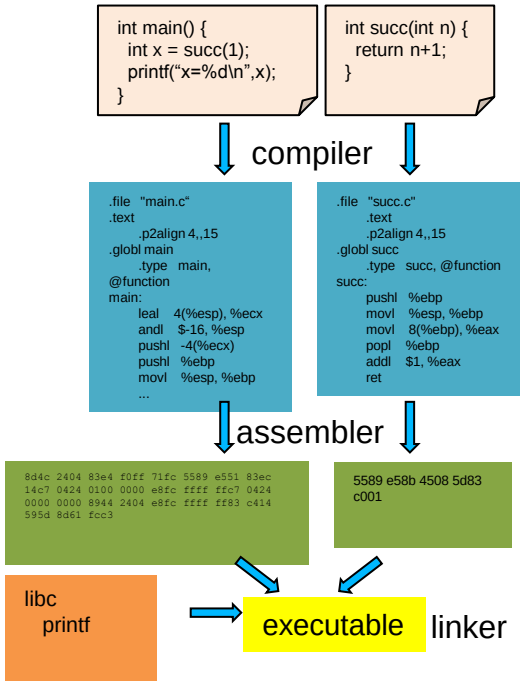
The Driver is your Friend




```
% gcc -v -o succ main.c succ.c
cc1 … main.c -mtune=generic -march=x86-64 -o /tmp/ccyCWXJg.s
as --64 -o /tmp/ccu4EbpF.o /tmp/ccyCWXJg.s
cc1 … succ.c -mtune=generic -march=x86-64 -o /tmp/ccyCWXJg.s
as --64 -o /tmp/ccS8HB63.o /tmp/ccyCWXJg.s
collect2 …-dynamic-linker /lib64/ld-linux-x86-64.so.2 -o succ
      /usr/lib64/crt1.o /usr/lib64/crti.o crtbegin.o
      -L/udd/alf/rohou/gcc-4.6.1/lib/gcc/x86_64-unknown-linux-gnu/4.6.1
      -L/udd/alf/rohou/gcc-4.6.1/lib64 –L/lib64 -L/usr/lib64 -L/udd/alf/rohou/gcc-4.6.1/lib
      /tmp/ccu4EbpF.o /tmp/ccS8HB63.o
      -lgcc_s -lc -lgcc
      /udd/alf/rohou/gcc-4.6.1/lib/gcc/x86_64-unknown-linux-gnu/4.6.1/crtend.o
      /usr/lib64/crtn.o
```

Compilation Toolchain

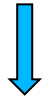
- Bottom-up
  - i.e. more or less chronologically
- Most useful binutils
- Compiler proper



as – assembler

- Mostly bi-univoque relation
  - syntax is more user-friendly
- Compute labels
- Deal with file format

```
.file   "main.c“
.text
        .p2align 4,,15
.globl main
        .type   main, @function
main:
        leal    4(%esp), %ecx
        andl    $-16, %esp
        pushl   -4(%ecx)
        pushl   %ebp
        movl    %esp, %ebp
        ...
```



```
8d4c 2404 83e4 f0ff 71fc 5589 e551 83ec
14c7 0424 0100 0000 e8fc ffff ffc7 0424
0000 0000 8944 2404 e8fc ffff ff83 c414
595d 8d61 fcc3
```

Libraries

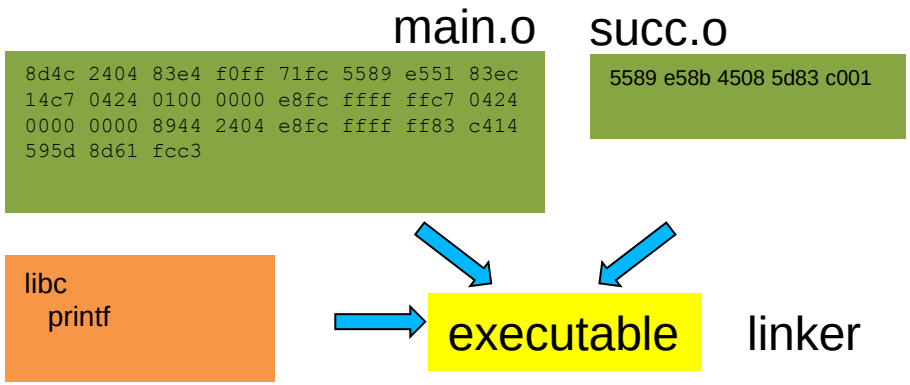
- Factorize commonly used functions/features
  - in Java: `import java.xxx`
- Code reuse, sharing
  - avoid rewrite
- In C: static and dynamic libraries
  - dynamic libraries reduce size of executable

ld – linker

```
int main() {
  int x = succ(1);
  printf("x=%d\n",x);
}
```

```
int succ(int n) {
  return n+1;
}
```

- Combines object files
- Resolve visible symbols
- Relocates data



GNU Binutils

- **as –** the GNU assembler
- **ld –** the GNU linker
- **addr2line** - Converts addresses into filenames and line numbers.
- **ar** - A utility for creating, modifying and extracting from archives.
- **c++filt** - Filter to demangle encoded C++ symbols.
- **dlltool** - Creates files for building and using DLLs.
- **gold** - A new, faster, ELF only linker, still in beta test.
- **gprof** - Displays profiling information.
- **nlmconv** - Converts object code into an NLM.
- **nm** - Lists symbols from object files.
- **objcopy** - Copys and translates object files.
- **objdump** - Displays information from object files.
- **ranlib** - Generates an index to the contents of an archive.
- **readelf** - Displays information from any ELF format object file.
- **size** - Lists the section sizes of an object or archive file.
- **strings** - Lists printable strings from files.
- **strip** - Discards symbols.
- **windmc** - A Windows compatible message compiler.
- **windres** - A compiler for Windows resource files.

objdump

- Display information from object files
  - ELF sections
  - code disassembly
  - …

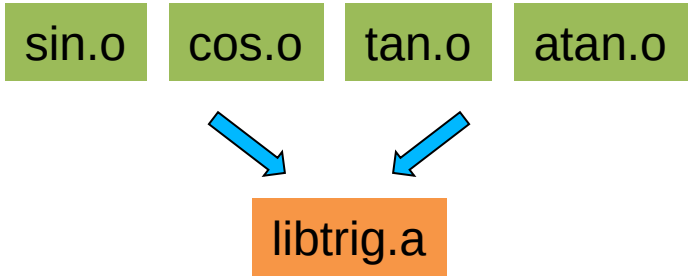
```
00000000004004a4 <succ>:
4004a4:   55              push   %rbp
4004a5:   48 89 e5        mov    %rsp,%rbp
4004a8:   89 7d fc        mov    %edi,-0x4(%rbp)
4004ab:   8b 45 fc        mov    -0x4(%rbp),%eax
4004ae:   83 c0 01        add    $0x1,%eax
4004b1:   5d              pop    %rbp
4004b2:   c3              retq
4004b3:   90              nop

00000000004004b4 <main>:
4004b4:   55              push   %rbp
4004b5:   48 89 e5        mov    %rsp,%rbp
4004b8:   bf bc 05 40 00  mov    $0x4005bc,%edi
4004bd:   e8 de fe ff ff  callq  4003a0 <puts@plt>
4004c2:   b8 00 00 00 00  mov    $0x0,%eax
4004c7:   5d              pop    %rbp
4004c8:   c3              retq
```

```
% objdump -h succ
erat:     file format elf64-x86-64
Sections:
Idx Name    Size      VMA                 LMA                 File off  Algn
 9 .init    00000018  0000000000400470  0000000000400470  00000470  2**2
            CONTENTS, ALLOC, LOAD, READONLY, CODE
11 .text    000002a8  0000000000400500  0000000000400500  00000500  2**4
            CONTENTS, ALLOC, LOAD, READONLY, CODE
13 .rodata  00000030  00000000004007b8  00000000004007b8  000007b8  2**3
            CONTENTS, ALLOC, LOAD, READONLY, DATA
22 .data    00000010  0000000000600aa8  0000000000600aa8  00000aa8  2**3
            CONTENTS, ALLOC, LOAD, DATA
```

ar, ranlib

- **ar** creates, modifies, and extracts from archives
  - combines object files
  - produces static library
- **ranlib** generates index to archive
  - faster linking



nm, strip, strings, size

- **nm** lists symbols from object files
- **strip** discards all symbols from object files
  - makes executable (slightly) smaller
  - cannot *see* symbols anymore (**nm** lists nothing)
- **strings** prints printable character sequences
  - at least 4 characters long by default
- **size** lists the section sizes

```
% strings succ
/lib64/ld-linux-x86-64.so.2
__gmon_start__
libc.so.6
printf
__libc_start_main
GLIBC_2.2.5
fff.
fffff.
l$ L
t$(L
|$0H
x = %d
```

```
% nm succ
…
00000000004004c0 T main
                 U printf@@GLIBC_2.2.5
00000000004004b0 T succ
```

gprof

- Produces an execution profile
- Useful to pinpoint long routines
  - at compile time, link with special library
  - at runtime, produce profile
  - post-mortem, run **gprof**

```
indx %time    self  children    called     name
             0.03    0.00       1/1           main [2]
[1]  100.0   0.03    0.00       1          compute_primes [1]
-----------------------------------------
                                              <spontaneous>
[2]  100.0   0.00    0.03                  main [2]
             0.03    0.00       1/1           compute_primes [1]
             0.00    0.00  921500/921500      print_other [3]
             0.00    0.00   78498/78498       print_prime [4]
-----------------------------------------
             0.00    0.00  921500/921500      main [2]
[3]    0.0   0.00    0.00  921500          print_other [3]
-----------------------------------------
             0.00    0.00   78498/78498       main [2]
[4]    0.0   0.00    0.00   78498          print_prime [4]
```

```
#include <stdio.h>
#define N 100

void compute_primes(int n,
                    char* sieve)
{
  int i, j;
  for(i=0; i<n; i++)
    sieve[i]=1;
  for(i=2; i<n; i++) {
    for(j=2*i; j<n; j+=i)
      sieve[j] = 0;
  }
}
void print_prime(int n) {
  printf("%d prime\n",n);
}
void print_other(int n) {
  printf("%d NOT prime\n",n);
}
int main() {
  char sieve[N];
  int  i;
  compute_primes(N, sieve);
  for(i=2; i<N; i++)
    if (sieve[i])
      print_prime(i);
    else print_other(i);
}
```

Dynamic Loader

- Not a *visible* tool
  - invoked by the system to start process
- fork/exec (seen already)
- Load libraries
- Load executable
- Patch relocations
- Execute

The Compiler

- Translate from high-level programming language to assembly

- In addition
  - optimization

```
int main() {
  int x = succ(1);
  printf("x=%d\n",x);
}
```

```
.file   "main.c"
.text
        .p2align 4,,15
.globl main
        .type   main, @function
main:
        leal    4(%esp), %ecx
        andl    $-16, %esp
        pushl   -4(%ecx)
        pushl   %ebp
        movl    %esp, %ebp
        ...
```

cpp

- Macro processor
  - #define
  - #include
  - #if #endif
- Invoked automatically by the C compiler

```
#include <stdio.h>

int foo(int n) {
#if DEBUG
  printf("n = %d\n", n);
#endif
  …
}
```

gcc –DDEBUG –o foo foo.c

Lexical Analysis

- Read source code as text file
- Produce tokens
- Recognize key language elements
  - reserved keywords
  - numbers
  - …

```
i f   ( c o n d )   {
    x   =   4 2 ;
}
e l s e   {
    y   =   2 . 4 ;
}
```

```
if  ( cond ) {
    x   =   42  ;
}                   INT
else            {
    y   =   2.4     ;
}                   FLOAT
```

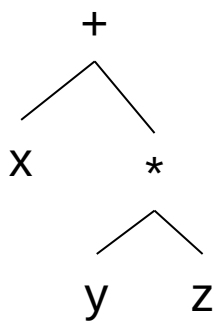
Parsing

- Start organizing the tokens
  - grammar
- Eclispe does it all the time to show errors
- Many tools to generate code
  - lex, yacc, ANTLR

S → S; S | ε
S → if E then S
S → if E then S else S
…
E → E + T | E – T | T
T → T * F | T / F | F
F → num
F → id
F → (E)

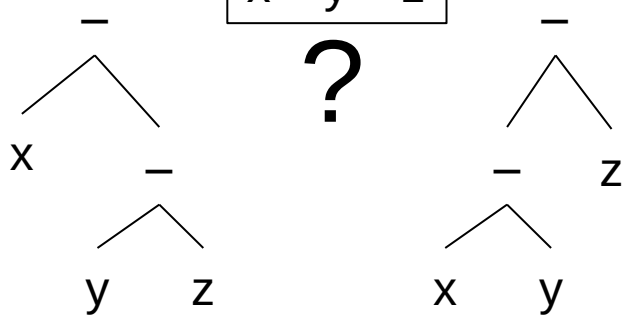
E → E + E | E – E | T
T → T * F | T / F | F
F → id

x + y * z



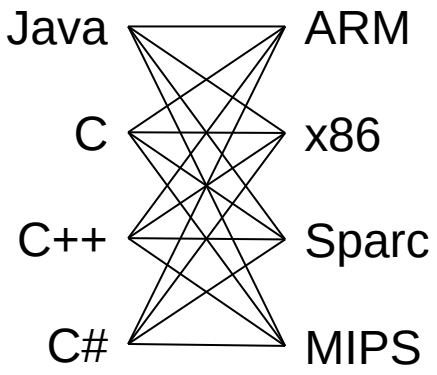
x – y – z

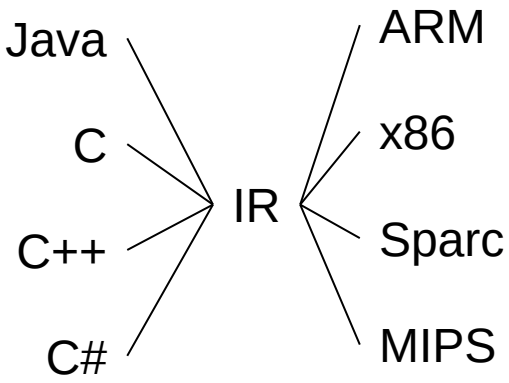
?



Intermediate Code

- Intermediate Representation
  - abstract machine language
  - independent of details of source language
- Key idea: for N languages, M machines
  - N + M < N.M
- Many examples
  - GCC: GIMPLE, RTL
  - Open64: WHIRL
  - recent: MinIR, Tirex, …





Optimizations

- Take advantage of
  - algebraic properties
  - instruction set characteristics
  - …
- Hundreds of optimizations
  - Common subexpression elimination
  - Tree balancing
  - Strength reduction
  - Loop unswitching
  - Dead code elimination

```
x = a * b + c
y = a * b + d
```

⇨

```
tmp = a * b
x = tmp + c
y = tmp + d
```

```
a = Math.pow(b, 2)
x = y * 16
```

⇨

```
a = b * b
x = y << 4
```

```
x = ((a + b) + c) + d
```

⇩

```
x = (a + b) + (c + d)
```

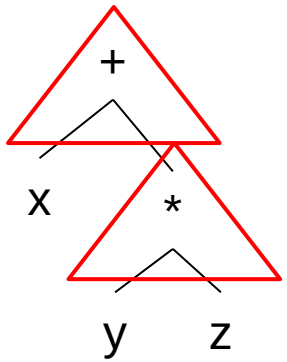
```
for(i=0; i < n; i++) {
  if (cond) {
    …
  }
}
```

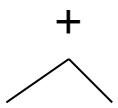
⇨

```
if (cond) {
  for(i=0; i < n; i++) {
    …
  }
}
```

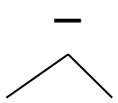
Instruction Selection

- From IR to actual instructions
- Cover the IR tree with tiles
  - tiles represent the instruction set
  - the tree is the optimized IR
- Minimize cost





add



sub

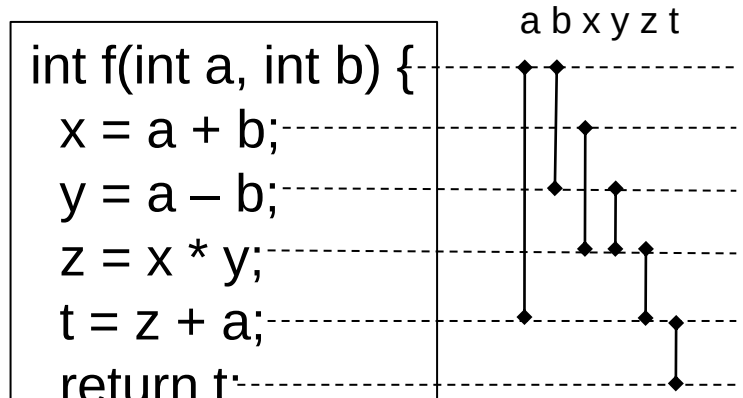
mul

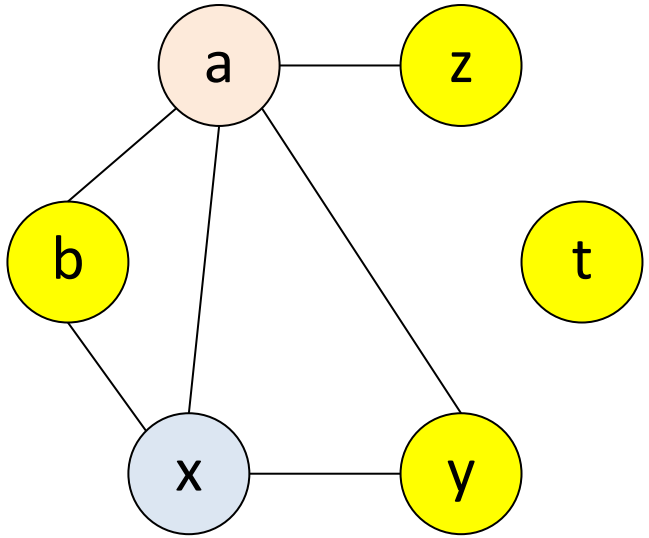
mul tmp ← y, z
add res ← x, tmp

Register Allocation

- Map large number of values to (small number of) machine registers
- Sub tasks
  - Liveness analysis
  - Interference graph
  - Graph coloring
  - Spilling
- but also
  - Precolored nodes
  - Specific constraints

```
int f(int a, int b) {
  x = a + b;
  y = a – b;
  z = x * y;
  t = z + a;
  return t;
}
```



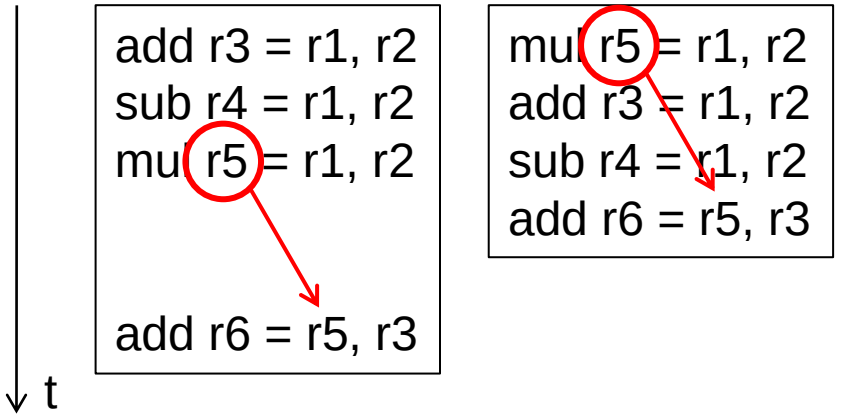



```
add r3 = r1, r2
sub r2 = r1, r2
mul r2 = r2, r3
add r2 = r2, r1
mov r1 = r2
ret
```

Scheduling

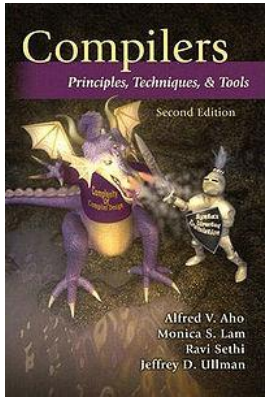
- Optimize order of instructions
  - better usage of processor pipeline
  - respect dependences
- Very important for VLIW and in-order processors
  - less so for out-of-order processors (x86)

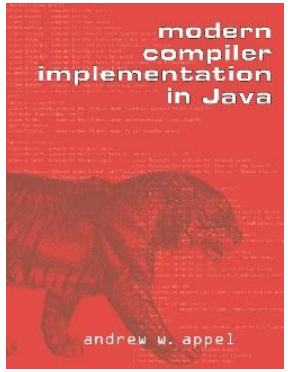
Example:
add takes 1 cycle
mul takes 3 cycles

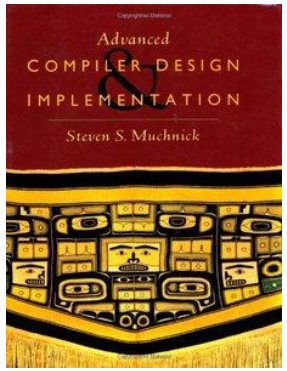


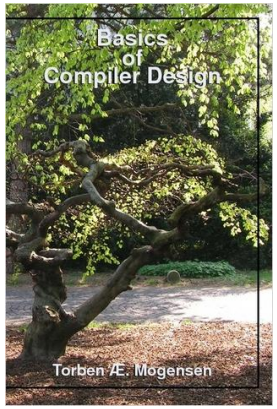
Some References

- "Compilers: Principles, Techniques, & Tools", Aho, Lam, Sethi, Ullman. Dragon Book.
- "Modern Compiler Implementation in Java", Andrew W. Appel.
- "Advanced Compiler Design and Implementation", Steven Muchnick.
- "Basics of Compiler Design", Torben Ægidius Mogensen, http://www.diku.dk/~torbenm/Basics









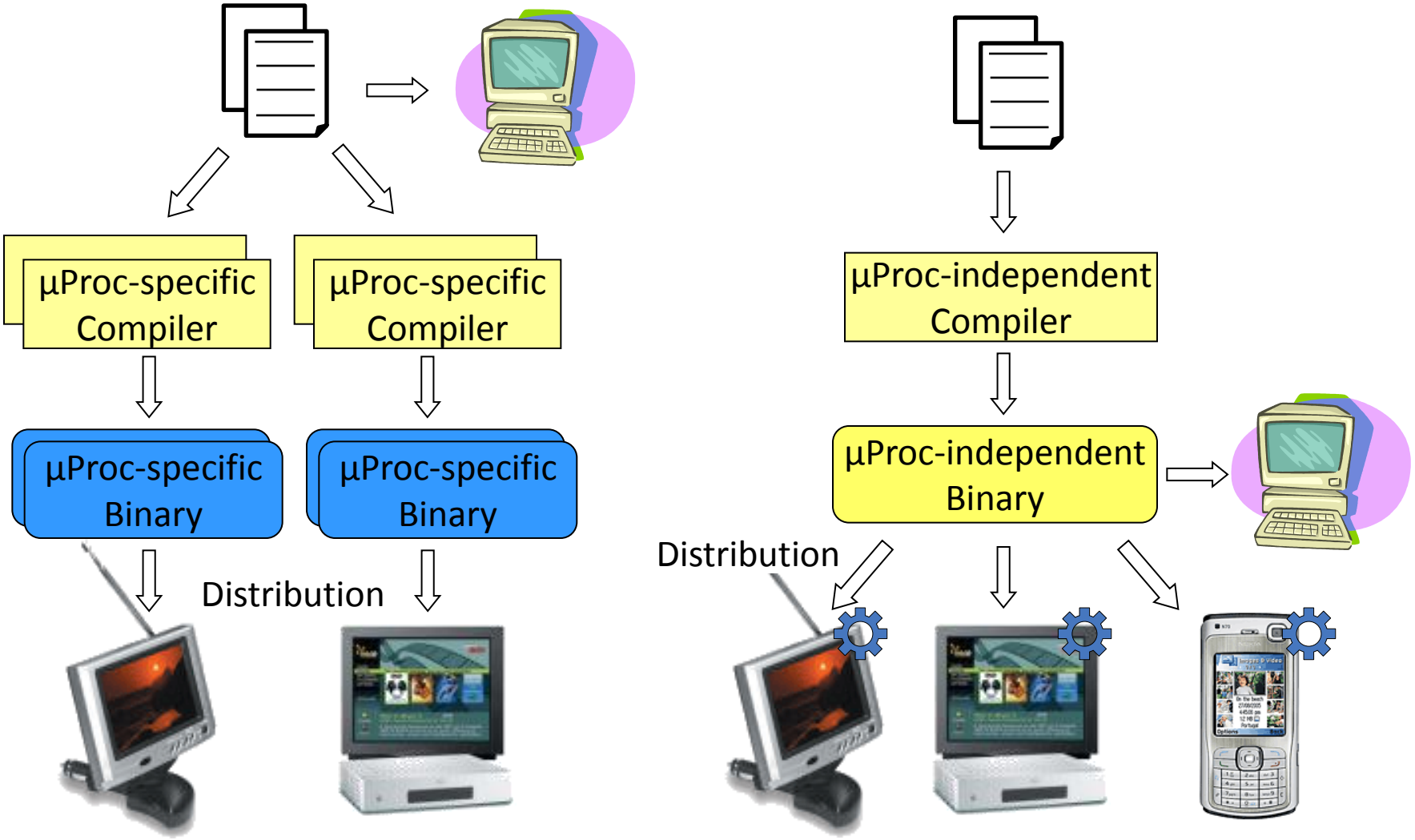
Developing software is difficult

- Programming languages provide abstractions…
  - dynamic memory allocation
  - object-oriented programming
  - strong typing
  - software components, etc.
- …to help programmers
  - reduced efforts
  - better error detection
  - better reuse (libraries, components)

The catch

- Abstractions have a performance cost
  - dynamic memory allocation: false dependencies
  - object-oriented programming: virtual dispatch, extra indirection, small methods
  - automatic memory management: need efficient garbage collection
  - late binding: need to deal with unknown information
  - reflection: deal with changing code
- (Good) support is provided in some kind of runtime
  - the Virtual Machine (VM)
- Not all aspects derive from the JIT/VM
  - for example: GC, object oriented language

Bytecodes and Just-in-time Compilers



Why?

- Deployment
  - simplify software engineering
  - addresses legacy problems
- Security, sandboxing
- Observability
  - for the application, the VM is OS, hardware, runtime, …
- Performance
  - because of additional information
  - compile only what is needed

Deployment

- Toolchain burden
  - maintain, upgrade
- Debug, validate
  - run what you validate
- Access to remote parts of the system
  - ISV
- Ship to future versions of the system
  - no worry about binary compatibility
  - no (less) worry about performance

Security, sandboxing

- Typical of VM (even though not a consequence of JIT)
- Limit access to physical resources
  - I/O, network
  - by policy
    - cf. `AndroidManifest.xml` and <uses-permission>
- Static analysis
  - array bounds
  - stack overflow, underflow

Obtain Even More Performance

- More information is available
  - OS
  - actual hardware
    - Nehalem vs. Core vs. Atom vs. ARM vs. ???
    - generate most efficient instructions (e.g. SSE4.2 if available)
  - whole program optimization
    - inline library functions
  - runtime constants
  - program input

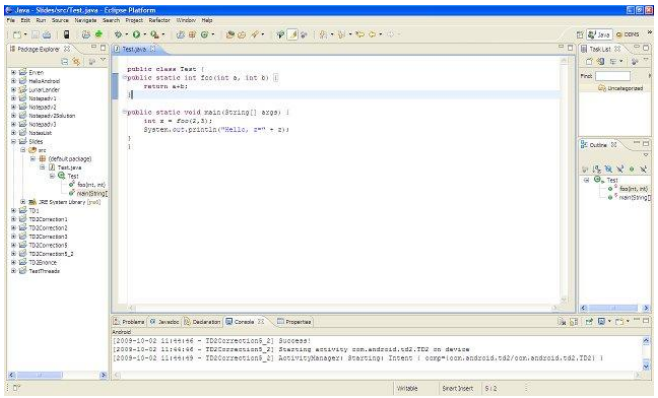
Challenges

- Compile time is part of runtime
- Memory shared between compiler and user
- Reverse engineering
  - obfuscation

History

- UCSD Pascal p-System mid-1970
- Smalltalk 1980
- CLisp 1987
- Sun's Self 1990
- Java 1995
- Transmeta's Crusoe and Code Morphing 2000 (x86 -> VLIW)
- LLVM initiated 2000
  - goes into Apple's Mac OS 10.5 'Leopard' OpenGL stack 2006
- CLI
  - .NET 1.0 2002, .NET 3.5 2007
  - ECMA standard 2001, ISO standard 2003

Java Compilation Flow



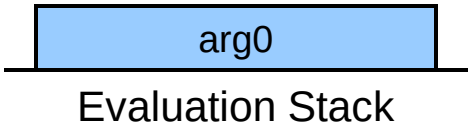
javac

Test.class

java

Evaluation Stack

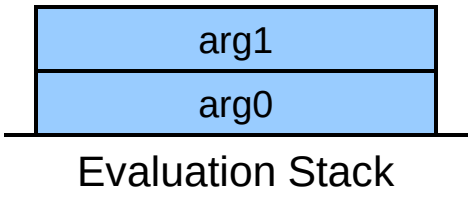
```
iload_0
```



- Potential Benefits:
  - Machine independence
  - Managed environment and security (against both malicious code and application faults)
  - Cross-language interoperability

Evaluation Stack

```
iload_0
iload_1
```



- Potential Benefits:
  - Machine independence
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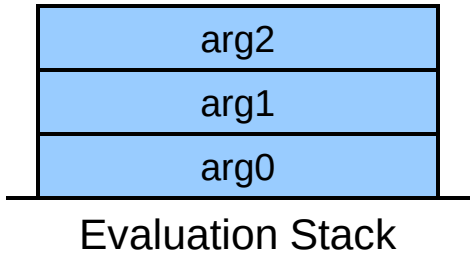
  - Cross-language interoperability

Evaluation Stack

```
iload_0
iload_1
iload_2
```



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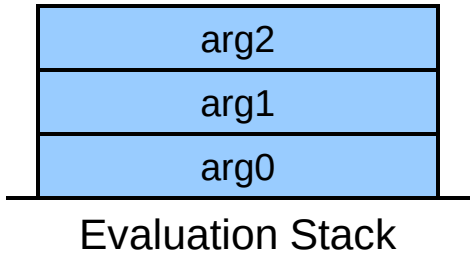
  - Cross-language interoperability

Evaluation Stack

```
iload_0
iload_1
iload_2
iadd
```



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Evaluation Stack

```
iload_0
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iload_2
iadd
```
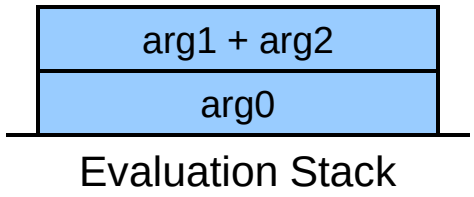
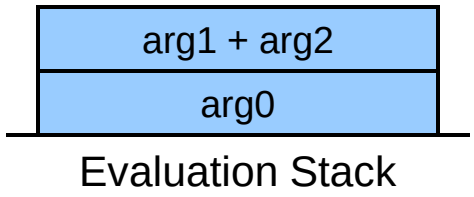



- Potential Benefits:
  - Machine independence
  - Managed environment and security (against both malicious code and application faults)
  - Cross-language interoperability

Evaluation Stack

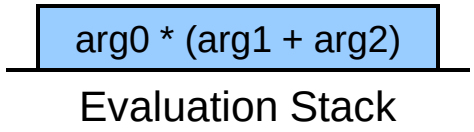
```
iload_0
iload_1
iload_2
iadd
imul
```



- Potential Benefits:
  - Machine independence
  - Managed environment and security (against both malicious code and application faults)
  - Cross-language interoperability

Evaluation Stack

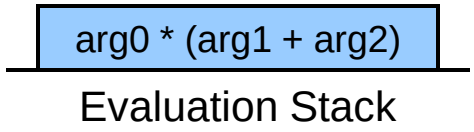
```
iload_0
iload_1
iload_2
iadd
imul
```



- Potential Benefits:
  - Machine independence
  - Managed environment and security (against both malicious code and application faults)
  - Cross-language interoperability

Evaluation Stack

```
iload_0
iload_1
iload_2
iadd
imul
ireturn
```



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Evaluation Stack

```
iload_0
iload_1
iload_2
iadd
imul
ireturn
```

- Potential Benefits:
  - Machine independence
  - Managed environment and security (against both malicious code and application faults)
  - Cross-language interoperability

Getting more concrete

- Example of Java bytecode
- Notice
  - evaluation stack
  - local variables
  - strongly typed

```
public class Test {
public static int foo(int a, int b) {
  return a+b;
}

public static void main(String[] args) {
  int z = foo(2,3);
  System.out.println("Hello, z=" + z);
}
}
```

```
public static int foo(int, int);
   0:   iload_0
   1:   iload_1
   2:   iadd
   3:   ireturn
public static void main(java.lang.String[]);
   0:   iconst_2
   1:   iconst_3
   2:   invokestatic  #2;       //foo:(II)I
   5:   istore_1
   6:   getstatic #3;           //Field System.out:Ljava/io/PrintStream;
   9:   new  #4;                //class java/lang/StringBuilder
   12:  dup
   13:  invokespecial  #5;  // java/lang/StringBuilder."<init>":()V
   16:  ldc  #6;                //String Hello, z=
   18:  invokevirtual  #7;    //StringBuilder.append;
   21:  iload_1
   22:  invokevirtual  #8;    //StringBuilder.append;
   25:  invokevirtual  #9;    //StringBuilder.toString;
   28:  invokevirtual  #10;  //java/io/PrintStream.println:()V
   31:  return
```

Interpreting

- Easy to implement
  - basically, a huge switch statement
  - Java implementations in cell phones
- No startup
- Slow execution

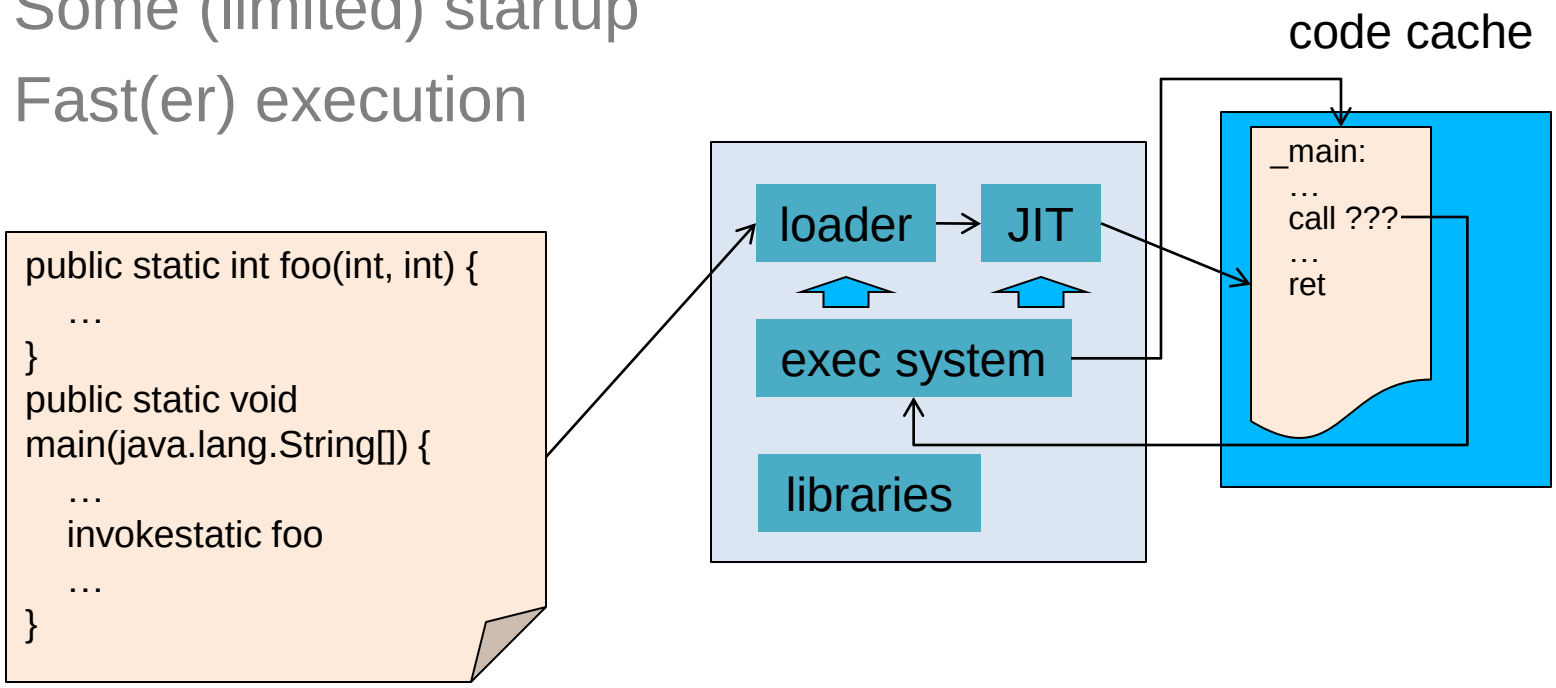
```
while (bytecode = read()) {
  switch(OPCODE(bytecode)) {
    case IADD:
       x = pop();
       y = pop();
       push(x+y);
      break;

    case ICONST_2:
      push(2);
      break;

    case INVOKESTATIC:
      …
      break;

    …
  }
}
```

AOT (Ahead Of Time) Compiling

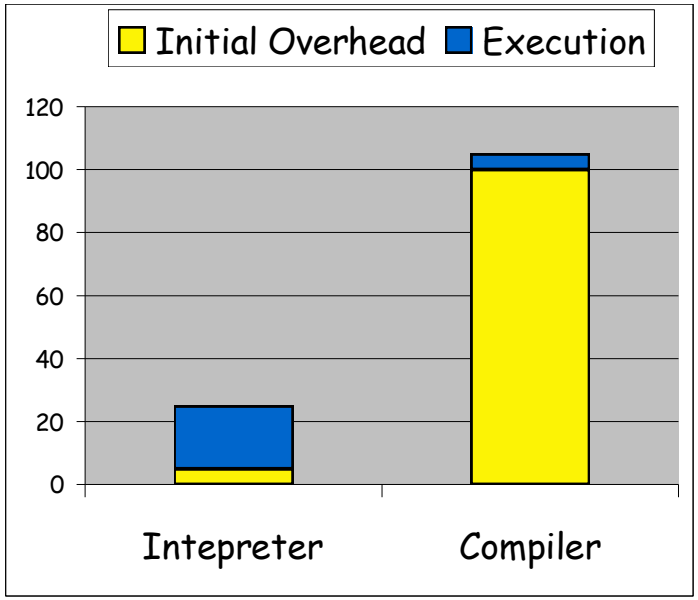
- Standard compilation, but happens on target platform
- Large startup
  - time to compile the bytecode to native code
- Fast execution
  - same as standard compilation

JIT (Just In Time) Compiling

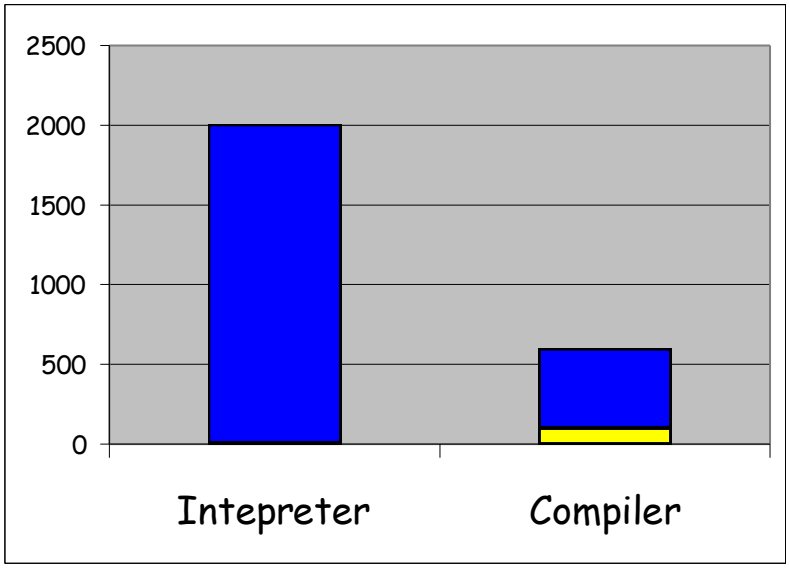
- Compile code Just-in-Time in memory
  - usually one function at a time
- Some (limited) startup
- Fast(er) execution



Interpretation vs JIT



Execution: 20 time units

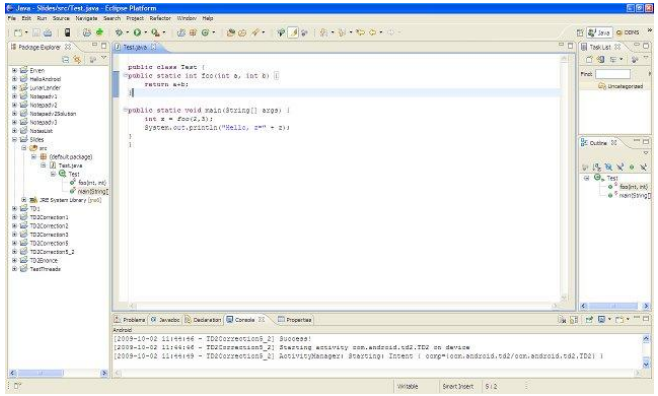


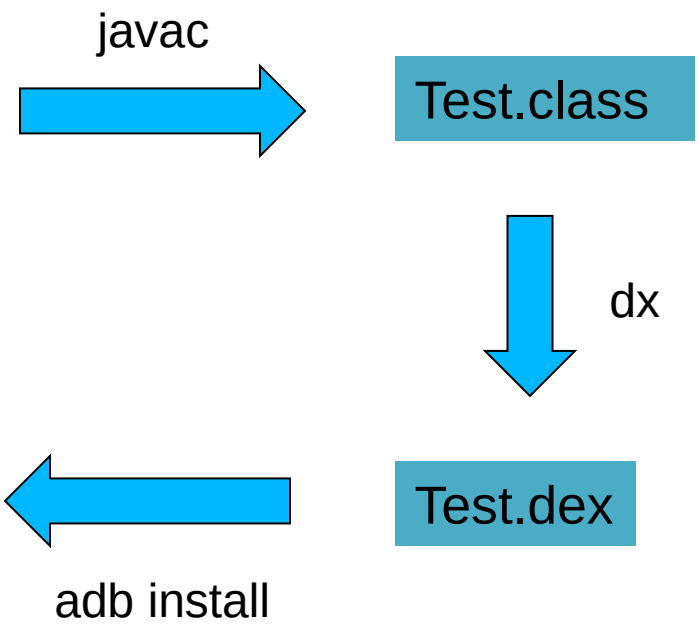
Execution: 2000 time units

[From Kathryn S McKinley, UT]

Android Compilation Flow

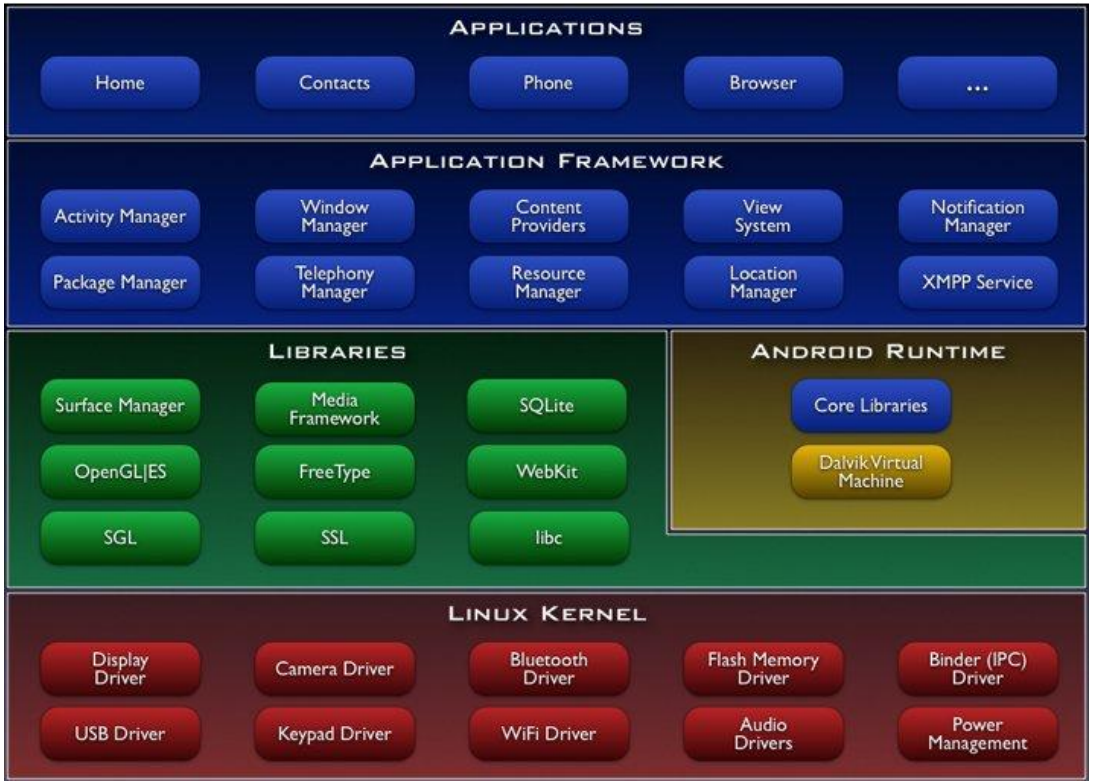
- Based on standard Java flow, but:
  - own bytecode, translated from Java
  - own libraries (not Java)
  - registers instead of evaluation stack





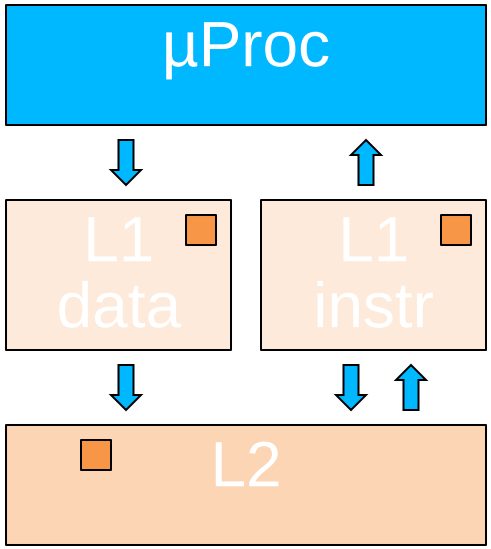
Android Runtime

- User code (.dex) used to be interpreted
  - Now JIT compiled
- Large set of libraries
- native code



Code Cache

- Store binary code (as if it was data)
- Need to handle hardware I/D cache
  - automatic on x86
  - careful on others
- New security mechanisms in Linux
  - protect against buffer overflow attacks
  - …but also against JIT compilers



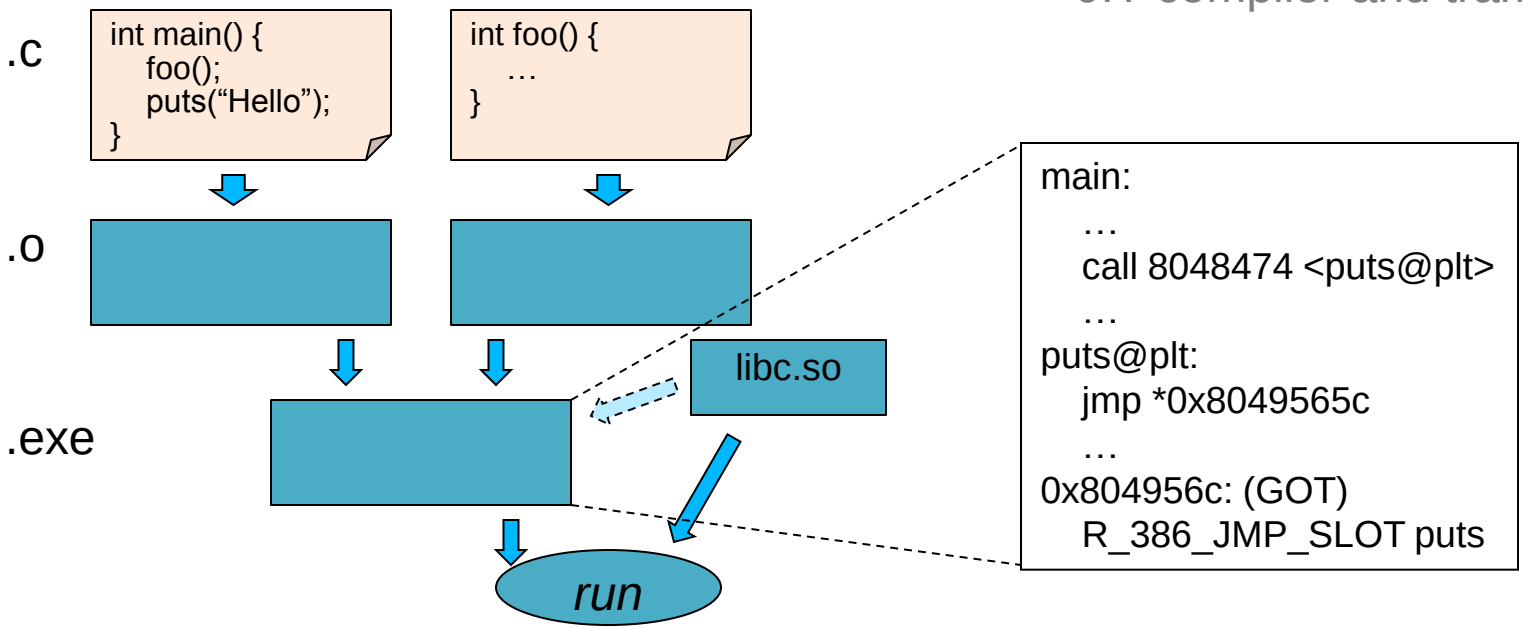
Tool chain: when JIT is easier

Standard compilation

- Deal with unknown addresses
  - relocations
  - assembler, linker, loader

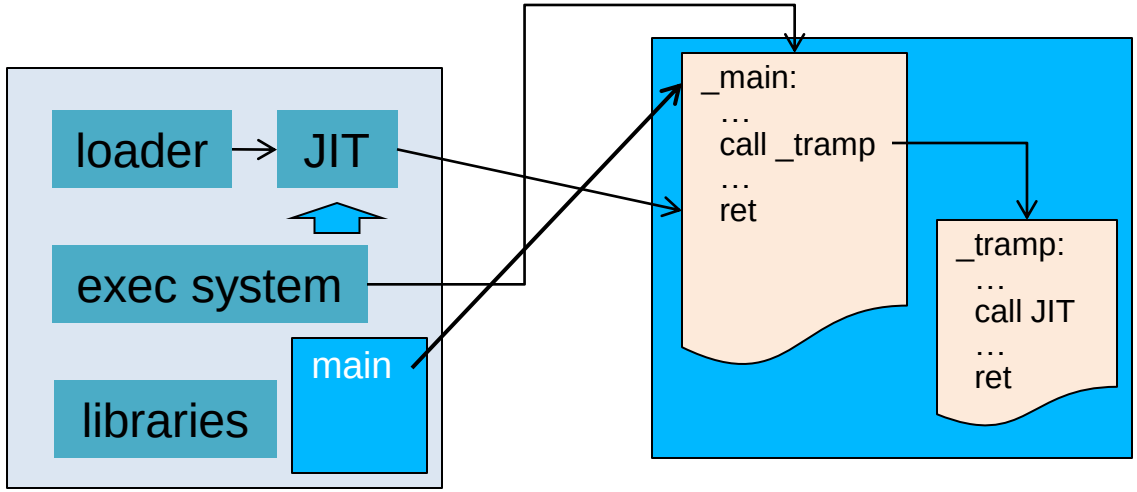
JIT compilation

- Code is generated when needed
  - addresses are known
  - JIT compiler and trampolines



Trampolines

- Hook to call back JIT when function is missing
- Can be used for additional services
  - e.g. profiling
- Remove when code becomes available



Runtime Opportunities

- Profiling, tracing
  - knowledge of application behavior
  - knowledge of environment (OS, actual target)
- Specialization
  - generate code that takes advantage of this knowledge
- Re-optimization
  - *hot* functions
  - phase changes

Selective Optimization

- Leverage the 90/10 rule (aka 80/20)
  - 90% of the time is spent in 10% of the code
  - optimize only the important part
- Strategy
  - initial unoptimized version
  - profile to detect *hot* functions
  - optimize them

Garbage Collection (GC)

- Simplify memory management
  - allocate
  - leave deallocation to the system
- Already present in Lisp, Smalltalk
- Today in Java, C#, Perl, Javascript,…

```
ptr = malloc(sizeof(*ptr));
…
free(ptr);
```

```
t = new Thread();
…
```

Garbage Collection: Principles

- Garbage: any object that will never be referenced again
  - problem: cannot be computed
- Garbage: any object that cannot be reached
  - ok: approximate liveness with reachability
- Basic idea
  - start from known live objects
  - follow all “links” and mark reachable objects as alive
  - reclaim unmarked objects

```
b = new Button();
   …
b = new Button(); /* kills previous */
```

Garbage Collection: Pros

- Simpler code
  - easier to understand
  - less error prone
  - faster
- Helps avoid
  - access to non-allocated memory
  - free already freed memory
  - memory leak
- Can make code faster
  - simpler code, easier to optimize
  - better locality with compacting GC

```
while (cond1) {
    if (cond2)
        ptr = malloc(sizeof(*ptr));
    foo(ptr);
}
 …
if (???)
  free(ptr);
```

```
while (cond1) {
    if (cond2)
        a = new A();
    foo(a);
}
 …
```

Garbage Collection: Cons

- Pause-time
- Difficult to control collection time
  - inappropriate for real-time applications
- Might require more memory
- Memory leaks more difficult to detect

Profiling

- What do you collect?
- When do you collect?
- How do you collect?
- What do you do with the collected data?

What data do you collect?

- Executed functions
- Executed paths, branch outcome
- Parameter values
- Loads and stores
- …

- Profile or trace?
- And consider overhead!

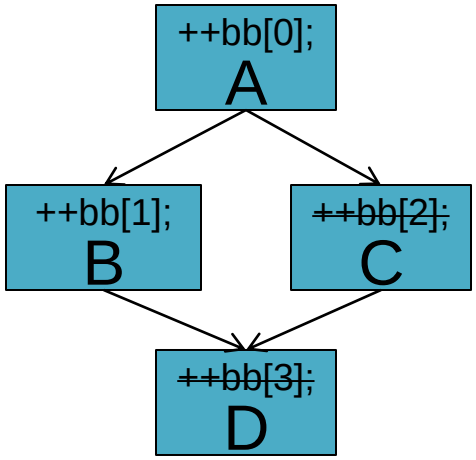
When do you collect the data?

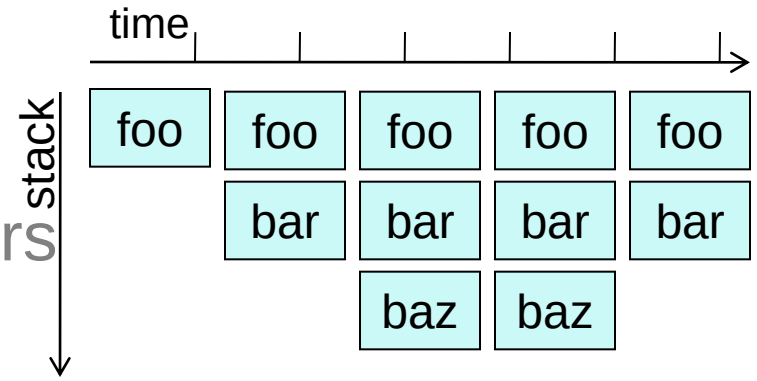
- Interpretation vs. JIT
- Continuous vs. intermittent
  - install and uninstall profiling code
- Phase based: early, steady state
- Tradeoff accuracy vs. overhead

How do you collect the data?

- Program instrumentation
  - function, basic block, edges, value
  - potential optimization (e.g. spanning tree)
- Sampling
  - running method, call stack
  - not deterministic, less accurate
- Hybrid
- Provided by VM
  - GC, class hierarchy
- Hardware performance counters
  - locality estimate, IPC, …

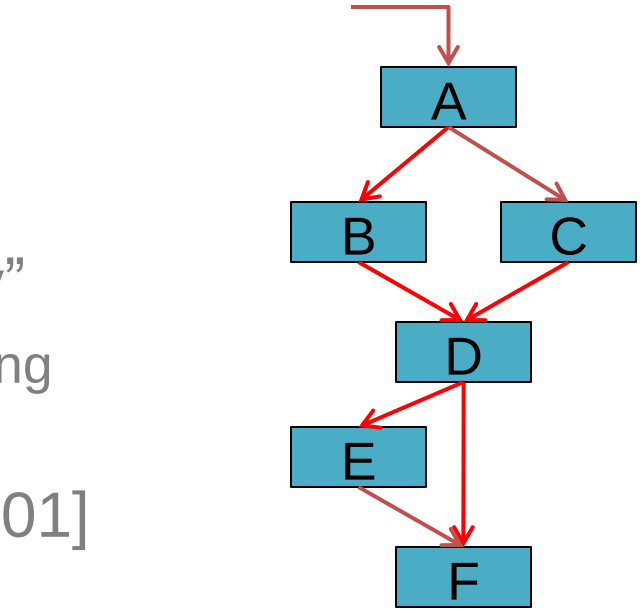
```
public int foo() {
  ++freq[FOO_ID];
  …
}
```

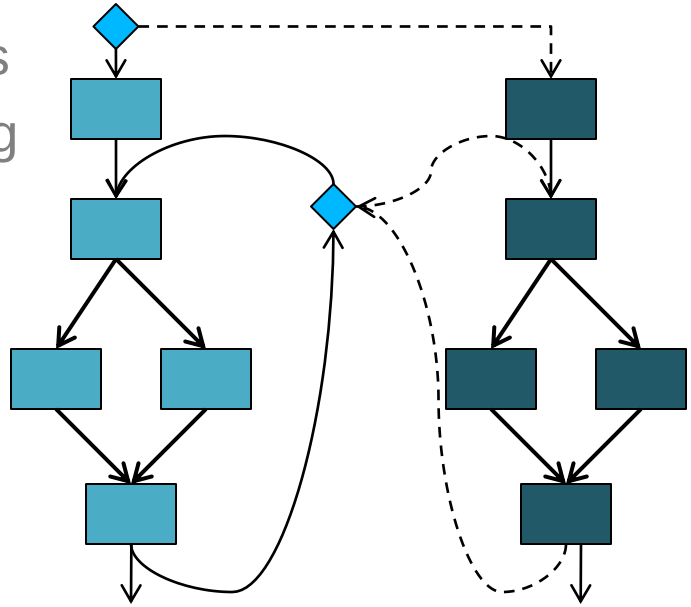




Control cost of profiling

- Do as much as possible “statically”
  - edge profiling with (minimum) spanning tree
- Duplicate method [ArnoldRyder2001]
  - one is profiled, one not
  - insert checks on entry and backedges
  - instrumented code returns to checking code





Control cost of profiling (cont'd)

- Ephemeral instrumentation [Traub2000]
  - patch/unpatch
  - example of conditional branches
  - patch at load-time, possibly at each page fault
  - unhook after some number of executions
  - rehook later to capture changing phases

```
    …
    beq $r1,tgt
    br stub
ft:
    …
tgt:
    …
```

```
stub:
    cmpeq $r1, 0, $t0
    process_branch()
    bne $t0, tgt
    br ft

[ total_count ]
[ taken_count ]
[ aggregate counters ]
```

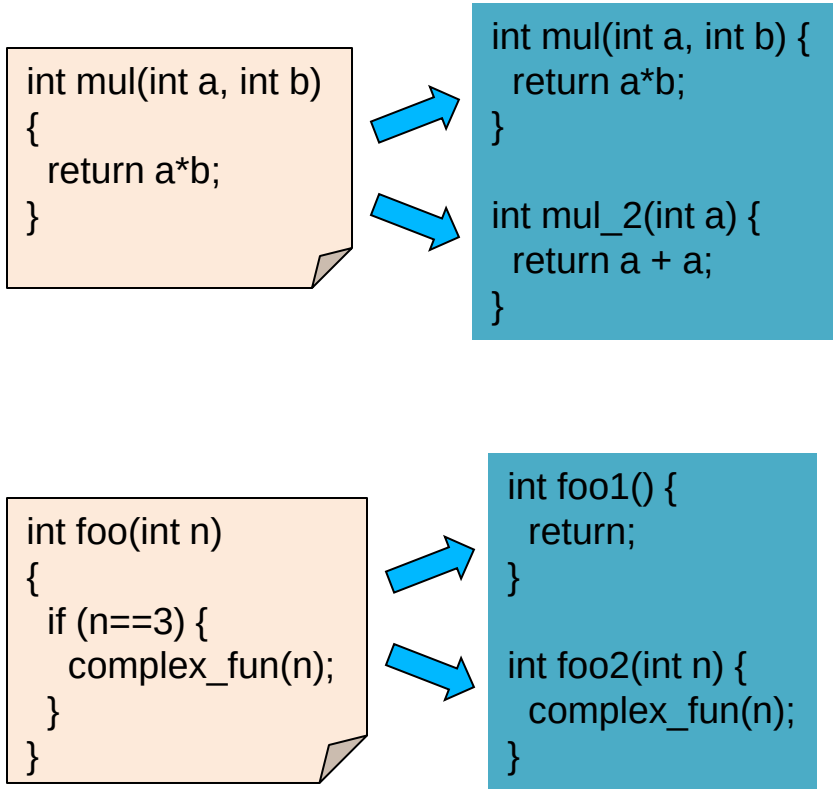
```
process_branch:
    total_count++
    taken_count += $t0
    if (total_count > unhook_constant)
        unhook_branch()
    return
```

What do you do with the data?

- Function specialization
- Inlining
- Code layout (hot/cold optimization)
- Multiversioning
- Loop unrolling
  - unroll *hot* loops
- Register allocation
  - spill in *cold* regions
- Stack allocate objects that escape only on cold paths

Specialization

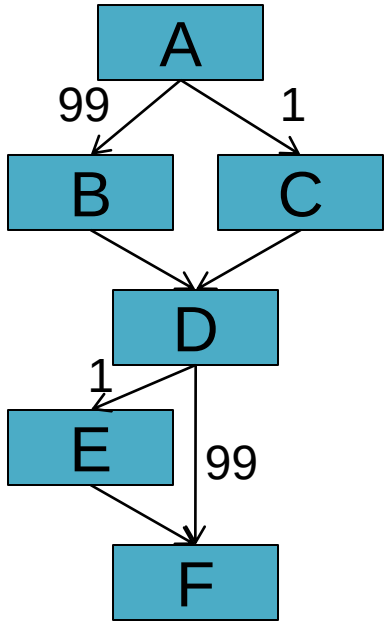
- Take advantage of frequent values
  - identify pseudo constants
  - optimize for particular values
  - enable other optimizations

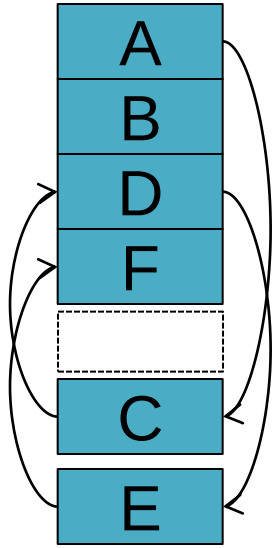


Code Layout

- Profile paths
- Layout for most frequent path (hot/cold)
  - good for spatial locality, prefetch
  - good for branch prediction

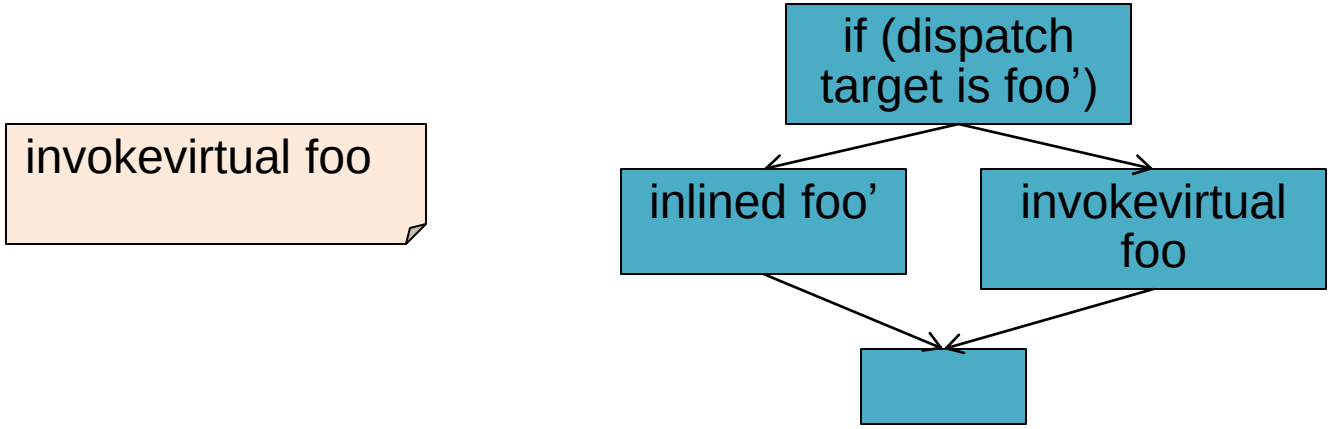
```
if (error) {
  result = NULL;
}
else {
  result =
}
if (error2) {
  errorCode = 1;
}
```





Multiversioning

- Static
  - emit multiple implementations
  - emit code to choose the best one at runtime
- Dynamic
  - generate ad hoc implementation on-the-fly
  - mostly deals with dispatch tables in OO languages



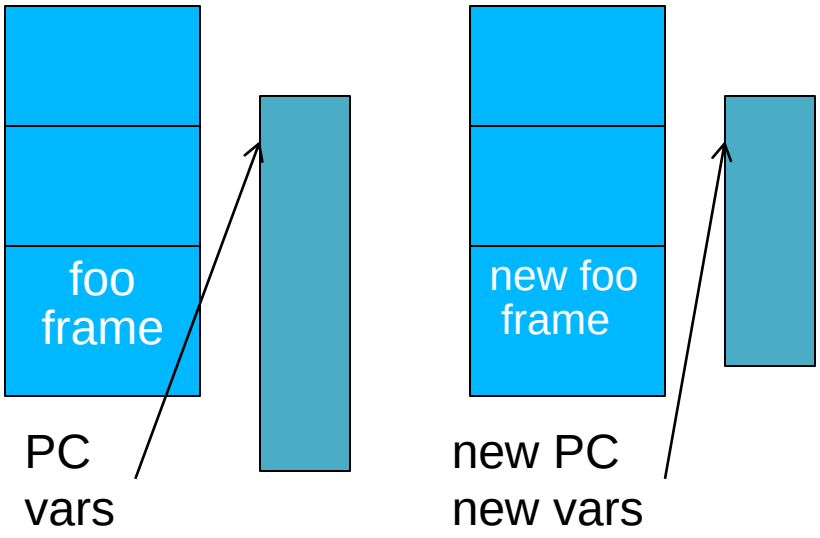
Re-optimization

- Keep monitoring for hot functions
  - or enable monitoring from time to time, sampling
- Re-optimize very hot ones
  - JIT again, using more aggressive optimizations
  - update in code cache
  - possibly use On-Stack-Replacement

On Stack Replacement

- Change code of running function
  - from interpreter to JIT
  - from low to high optimization level
  - adjust to changing behavior
- Generate program states
  - locations of local variables
  - program counter
- At replacement time
  - generate new stack frame
  - generate new code
  - restore state
  - transfer execution

```
public static int main(String[] args)
{
  for(int i=0; i<1000000; ++i) {
    /* do something */
  }
}
```



JIT/VM Interaction

- The JIT compiler is only a part of the VM
  - or the VM is only the support of the JIT?
- VM services
  - memory management (GC)
  - exception handling
  - type checking
  - interface to OS and hardware
    - dynamic linking
    - hardware counters, traps, signals
- Codesign is necessary

JIT support for VM

- For memory management
  - roots locations (registers, stack, etc.)
  - types
  - where GC can occur
- For exceptions
  - location of try/catch blocks in generated code
- For debugging
  - mapping bytecode - source code

VM support for JIT

- Memory allocation
  - inline frequent allocator
  - need to expose internal details
- NULL pointer check
  - rely on OS signals
- Generated code relies on runtime
  - “optimized” API
  - direct access to data structures

JIT/VM Tight Integration

Pros

- Performance of the runtime
- Allows optimized generated code
  - inlined code
  - direct access to data structures

Cons

- Software engineering
  - intricate software components
  - unspecified interfaces
  - maintenance, debug
  - no reuse of JIT in other VM