CS 4120
Introduction to Compilers

Andrew Myers
Cornell University

Lecture 19: Introduction to Optimization

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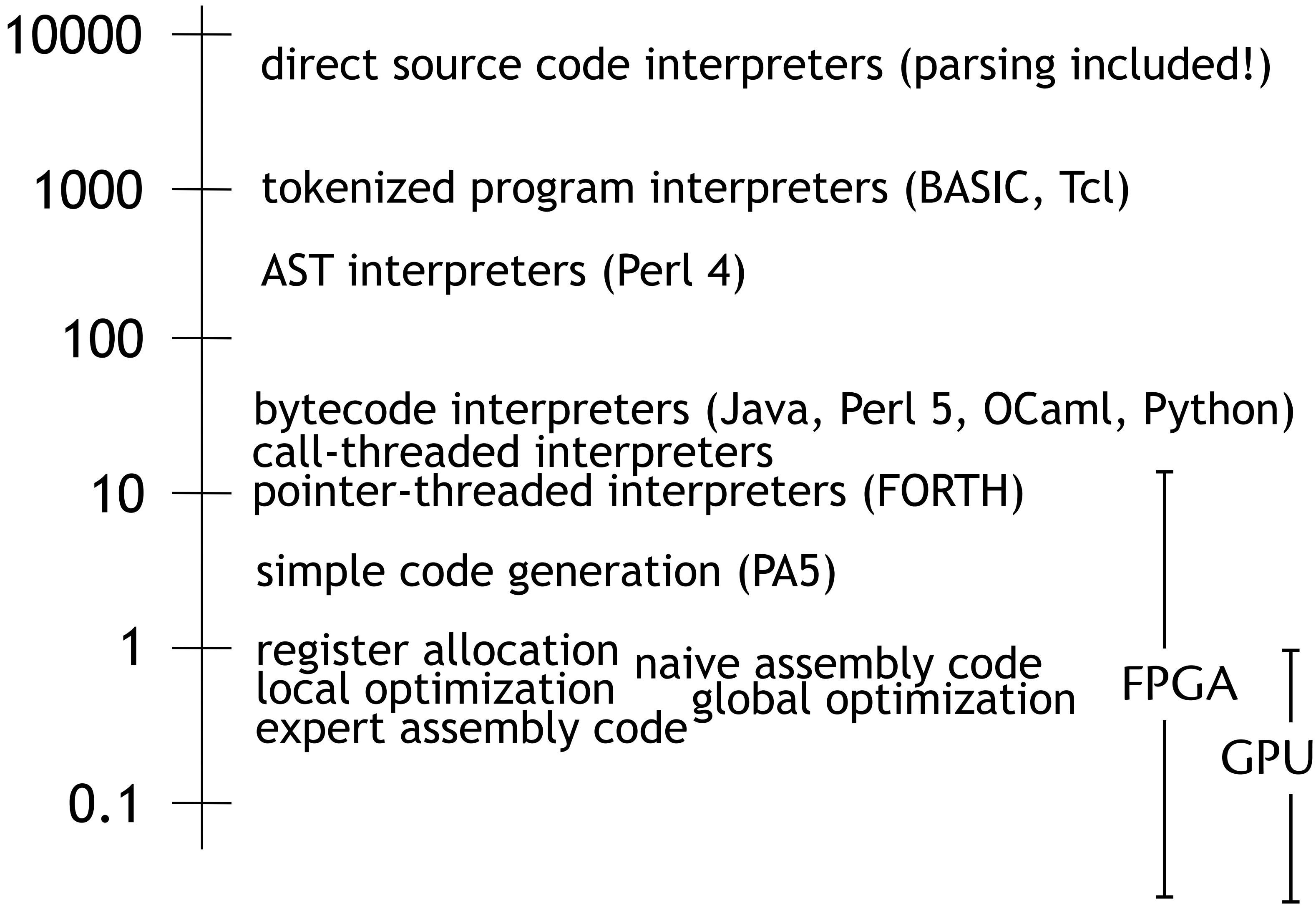
Optimization

- Next topic: how to generate better code through **optimization.**
- This course covers the most valuable and straightforward optimizations – much more to learn!
  - Other sources:
    - Appel, Dragon book
    - Muchnick: 10 chapters
    - Cooper and Torczon

How fast can you go?



Goal of optimization

- Modular, high-level source code + expert assembly-code performance.
- Can't change meaning of program to behavior not allowed by source.
- Different goals:
  - space optimization: reduce memory use
  - time optimization: reduce execution time
  - power optimization: reduce power usage

Why do we need optimization?

- Programmers may write suboptimal code for clarity.
- Source language may make it hard to avoid redundant computation

```
a[i][j] = a[i][j] + 1
```

- Architectural independence
- Modern architectures assume optimization—hard to optimize by hand!

Example

```
/* Returns: y * z (the hard way)
 * Requires: y is nonnegative.
 */
int f(int y, int z) {
    int sum = 0;
    for (int i = 0; i < y; i++) {
        sum += z;
    }
    return sum;
}
```

Where to optimize?

- Usual goal: improve time performance
- But: many optimizations trade off space vs. time.
- *Example:* loop unrolling replaces a loop body with *N* copies.
  - Increasing code space speeds up one loop but slows rest of program down a little.
  - Frequently executed loops with many iterations: space/time tradeoff is generally a win.
  - Infrequently executed code: optimize code space at expense of time, saving space in instruction cache, TLB
- Time–space tradeoffs may never pay off!
- Focus of optimization: program **hot spots**

Safety

- Possible opportunity for **loop-invariant code motion:**

```
while (b) {
        z = y/x; // x, y not assigned in loop
        …
}
```

- Transformation: hoist invariant code out of loop:

```
z = y/x;
while (b) {
        …
}
```

Preserves meaning?
Faster?

How to write fast programs

1. Pick the right algorithms and data structures: design for few operations, small memory footprint and good locality
2. Turn on optimization and **profile** to figure out program hot spots.
3. Evaluate whether design works; if so…
4. Tweak source code until optimizer does “the right thing” to machine code.
   – **understanding optimizers helps!**

Structure of an optimization

- Optimization is a *code transformation*
- Applied at some stage of compiler (HIR, MIR, LIR)
- In general, requires some analysis:
  - *safety analysis* to determine whether transformation might change meaning
  - *cost analysis* to determine whether expected to improve performance

When to apply optimization

HIR	AST	Inlining
		Specialization
	IR	Constant folding
		Constant propagation
		Value numbering
MIR	Lowered IR	Dead code elimination
		Loop-invariant code motion
		Common sub-expression elimination
		Strength reduction
	Abstract Assembly	Constant folding & propagation **(again)**
		Branch prediction/optimization
LIR		Register allocation
		Loop unrolling
	Assembly	Cache optimization
		Peephole optimizations

Register allocation

- Goal: convert abstract assembly (infinite no. of registers) into real assembly (6 registers)

```
mov t1,t2
add t1,[rbp–8]
mov t3,[rbp-16]
mov t4,t3
cmp t1,t4
```

```
mov rax, rbx
add rax, [rbp-8]
mov rbx, [rbp-16]

cmp rax, rbx
```

Try to reuse registers aggressively (e.g., **`rbx = t2, t3, t4`**)

- Coalesce registers (`t3`, `t4`) to eliminate **`mov`**'s
- In general, must **spill** some temporaries to stack

Constant folding

- Idea: if operands are known at compile time, evaluate at compile time when possible.

```
int x = (2 + 3)*4*y;  ⇒  int x = 5*4*y;
                      ⇒  int x = 20*y;
```

- Easy and useful at every compilation stage
  - Constant expressions are created by translation and by other optimizations

```
a[2] ⇒ MEM(TEMP(a) + 2*8)
     ⇒ MEM(TEMP(a) + 16)
```

Constant-folding conditionals

```
if (true) S ⇒ S
if (false) S ⇒ {}
if (true) S else S’ ⇒ S
if (false) S else S’ ⇒ S’
while (false) S ⇒ {}
if (2 > 3) S ⇒ if (false) S ⇒ {}
if (DEBUG) { println(“…”); }
```

Constant propagation

- If value of variable is known to be a constant, replace use of variable with constant
- Value of variable must be propagated forward from point of assignment

```
x:int = 5;
y:int = x*2;  y:int = 5*2;  y:int = 10;
int z = a[y]; // = MEM(TEMP(a) + y*8)
                = MEM(TEMP(a) + 80)
```

- Interleave with constant folding!

Copy propagation

- Given assignment **x = y**, replace subsequent uses of **x** with **y**
- May make **x** a dead variable, result in dead code
- Need to determine where copies of **y** (definitely) propagate to

```
x = y
if (x > 1)
  x = x * f(x - 1)
```

⇒

```
x = y        (struck through)
if (y > 1) {
  x = y * f(y - 1)
```

~~x = y~~ *dead code*

Algebraic simplification

More general form of constant folding: exploit simplification rules

identities

a * 1 ⇒ a   a * 0 ⇒ 0

a + 0 ⇒ a

b || false ⇒ b   b && true ⇒ b

reassociation

(a + 1) + 2 ⇒ a + (1 + 2) ⇒ a+3

strength reduction

a * 4 ⇒ a shl 2

a * 7 ⇒ (a shl 3) − a

a / 32767 ⇒ a shr 15 + a shr 30 + a shr 45 + a shr 60

With floating point and overflow, algebraic identities may give wrong or less precise answers.

- E.g., (a+b)+c = a+(b+c) for Java int but not C int
- (a+b)+c ≠ a+(b+c) in floating point (`float`, `double`) if a, b small.

Redundancy Elimination

- Common Subexpression Elimination (CSE) combines redundant computations

a[i] = a[i] + 1
⇒ [a+i*8] = [a+i*8] + 1
⇒ t1 = a + i*8; [t1] = [t1]+1

- Need to determine that expression always has same value in both places

b[j]=a[i]+1; c[k]=a[i] ⇒ t1=a[i]; b[j]=t1+1; c[k]=t1 ?

Unreachable code elimination

- Basic blocks not contained by any trace leading from starting basic block are **unreachable** and can be eliminated
- Performed at canonical IR or assembly code levels
- Reductions in code size improve cache, TLB performance.

≠ dead code elimination ("dead" = reached but useless)

Dead code elimination

If side effect of a statement can never be observed, can eliminate the statement:

```
x = y*y;        // dead!
...             // x unused
x = z*z;
```

⇒

```
...
x = z*z;
```

- **Dead variable:** if never read after defn. (exc. to update other dead vars)

```
{ int i;
  while (m<n) { m++; i = i+1}
}
```

⇒

```
while (m<n) {m++}
```

Other optimizations create dead statements, variables

Inlining

- Replace a function call with the body of the function:

```
f(a: int):int = { b:int=1;   n:int = 0
               while (n<a) {b = 2*b; return b }}
g(x: int):int  = { return 1 + f(x) }
⇒ g(x:int):int = { fx:int { a:int = x
                  { b:int=1; n:int=0;
                    while (n<a) { b = 2*b; fx=b }}
               return 1 + fx; }
```

- Best done on HIR
- Inlining methods is more difficult — there can only be one f
- May need to rename variables to avoid **name capture**
  —what if f refers to a global variable x?

Specialization

Idea: create specialized versions of functions (or methods) that are called from different places w/ different args

```
class A implements I { m( ) {…} }
class B implements I { m( ) {…} }
f(x: I) { x.m( ); } // don’t know which m
a = new A(); f(a)  // know it’s A.m
b = new B(); f(b)  // know it’s B.m
```

- Can inline methods when implementation is known
  —e.g., if only one implementing class or exact class is known
- Can specialize inherited methods to receiver class, avoid dispatching on method calls (e.g., HotSpot JIT)

Loops

- Program *hot spots* are usually loops (exceptions: OS kernels, compilers)
- Most execution time in most programs is spent in loops: 90/10 is typical.
- Loop optimizations: important, effective, and numerous

Loop-invariant code motion

- A form of redundancy elimination
- Idea: **hoist** unchanging expressions before loop
  - must have no externally visible side effect

```
for (i = 0; i < a.length; i++) {
  // a not assigned in loop
}
```

hoisted loop-invariant expression

```
t1 = a.length;
for (i = 0; i < t1; i++) {
  …
}
```

Strength reduction

- Replace expensive operations (*,/) by cheap ones (+, –) using **dependent induction variable**

```
for (int i = 0; i < n; i++) {
  a[i*3] = 1;
}
```

```
int j = 0;
for (int i = 0; i < n; i++) {
     a[j] = 1; j = j+3;
}
```

*j == 3*i*

Loop unrolling

- Branches are expensive; **unroll** loop to avoid them:

```
for (i = 0; i<n; i++) { S; }
```

```
for (i = 0; i < n-3; i+=4) {S; S; S; S;}
for (      ; i < n  ; i++) { S; }
```

- Eliminate up to ¾ of conditional branches!
- Creates more straight-line code to optimize
- Space–time tradeoff: not a good idea for large `S` or small `n`.

Summary

- Many useful optimizations that can transform code to make it faster/smaller/...
- Whole is greater than sum of parts: optimizations should be applied together, sometimes more than once, at different levels.
- The hard problem: when are optimizations **safe** and when are they **effective**?

$\Rightarrow$ **Dataflow analysis**

$\Rightarrow$ **Control flow analysis**

$\Rightarrow$ **Pointer analysis**