CSE 401/M501 – Compilers

Survey of Code Optimizations

Hal Perkins

Autumn 2022

Administrivia

- Semantics/type checking due Thursday night
  - Be sure to re-read MiniJava project overview and semantics assignment before final tagging to look for anything missed or any not-quite-right assumptions
  - 2 late days max *if* your group has them
    - If there are any really unusual situations, send mail to cse401-staff
- CSE M 501 “project extras” requirements / suggestions posted
  - Figure out what you want to do and discuss with instructor, preferably by end of this week.
- Sections this week: details of codegen for project

Administrivia (added Wed.)

- Semantics/type-checking due Tomorrow night
  - Be sure to re-read MiniJava overview and semantics assignment when you think your’re done
- Sections tomorrow: details of codegen for project
  - We’ll start this today
- Code gen assignment posted end of week, due Thur. after Thanksgiving

Administrivia (added Fri.)

- Plan on having class Wed. before 🦃. Want to finish dataflow before the break.
- You should get `System.out.println(42)` codegen compiled and running by Monday
  - Hardest part of this is getting past the psychological hurdle of getting started. ☺
  - Should be plenty of time to finish by Dec. 1 deadline if you start now and add things regularly.

Agenda

- Survey some code “optimizations” (improvements)
  - Get a feel for what’s possible
- Some organizing concepts
  - Basic blocks
  - Control-flow and dataflow graph
  - Analysis vs. transformation

Optimizations

- Use added passes to identify inefficiencies in intermediate or target code
- Replace with equivalent but better sequences
  - Equivalent = “has same externally visible behavior”
  - Better can mean many things: faster, smaller, use less power, …
- “Optimize” overly optimistic: “usually improve” is generally more accurate
  - And “clever” programmers can outwit you!

An example

Optimizer note: typically, assignment of actual registers happens later; we assume as many “pseudo registers” tn as we need here; using a *new* tn every time simplifies tracking.

```
x = a[i] + b[2];
c[i] = x - 5;
```

```
t1 = *(fp + ioffset);   // i
t2 = t1 * 4;
t3 = fp + t2;
t4 = *(t3 + aoffset);   // a[i]
t5 = 2;
t6 = t5 * 4;
t7 = fp + t6;
t8 = *(t7 + boffset);   // b[2]
t9 = t4 + t8;
*(fp + xoffset) = t9;   // x = …
t10 = *(fp + xoffset); // x
t11 = 5;
t12 = t10 - t11;
t13 = *(fp + ioffset); // i
t14 = t13 * 4;
t15 = fp + t14;
*(t15 + coffset) = t12; // c[i] := …
```

An example

```
x = a[i] + b[2];
c[i] = x - 5;
```

Strength reduction: shift often cheaper than multiply

```
t1 = *(fp + ioffset);   // i
t2 = t1 << 2;   // was t1 * 4
t3 = fp + t2;
t4 = *(t3 + aoffset);   // a[i]
t5 = 2;
t6 = t5 << 2;   // was t5 * 4
t7 = fp + t6;
t8 = *(t7 + boffset);   // b[2]
t9 = t4 + t8;
*(fp + xoffset) = t9;   // x = …
t10 = *(fp + xoffset); // x
t11 = 5;
t12 = t10 - t11;
t13 = *(fp + ioffset); // i
t14 = t13 << 2; // was t13 * 4
t15 = fp + t14;
*(t15 + coffset) = t12; // c[i] := …
```

An example

```
x = a[i] + b[2];
c[i] = x - 5;
```

```
t1 = *(fp + ioffset);   // i
t2 = t1 << 2;
t3 = fp + t2;
t4 = *(t3 + aoffset);   // a[i]
t5 = 2;
t6 = 2 << 2;   // was t5 << 2
t7 = fp + t6;
t8 = *(t7 + boffset);   // b[2]
t9 = t4 + t8;
*(fp + xoffset) = t9;   // x = …
t10 = *(fp + xoffset); // x
t11 = 5;
t12 = t10 - 5;   // was t10 - t11
t13 = *(fp + ioffset); // i
t14 = t13 << 2;
t15 = fp + t14;
*(t15 + coffset) = t12; // c[i] := …
```

Constant propagation: replace variables with known constant values

An example

```
x = a[i] + b[2];
c[i] = x - 5;
```

```
t1 = *(fp + ioffset);   // i
t2 = t1 << 2;
t3 = fp + t2;
t4 = *(t3 + aoffset);   // a[i]
~~t5 = 2;~~
t6 = 2 << 2;
t7 = fp + t6;
t8 = *(t7 + boffset);   // b[2]
t9 = t4 + t8;
*(fp + xoffset) = t9;   // x = …
t10 = *(fp + xoffset); // x
~~t11 = 5;~~
t12 = t10 - 5;
t13 = *(fp + ioffset); // i
t14 = t13 << 2;
t15 = fp + t14;
*(t15 + coffset) = t12; // c[i] := …
```

Dead store (or dead assignment) elimination: remove assignments to provably unused variables

An example

```
x = a[i] + b[2];
c[i] = x - 5;
```

Constant folding: statically compute operations with known constant values

```
t1 = *(fp + ioffset);   // i
t2 = t1 << 2;
t3 = fp + t2;
t4 = *(t3 + aoffset);   // a[i]
t6 = 8;   // was 2 << 2
t7 = fp + t6;
t8 = *(t7 + boffset);   // b[2]
t9 = t4 + t8;
*(fp + xoffset) = t9;   // x = …
t10 = *(fp + xoffset); // x
t12 = t10 - 5;
t13 = *(fp + ioffset); // i
t14 = t13 << 2;
t15 = fp + t14;
*(t15 + coffset) = t12; // c[i] := …
```

An example

```
x = a[i] + b[2];
c[i] = x - 5;
```

Constant propagation then dead store elimination

```
t1 = *(fp + ioffset);   // i
t2 = t1 << 2;
t3 = fp + t2;
t4 = *(t3 + aoffset);   // a[i]
~~t6 = 8;~~
t7 = fp + 8;   // was fp + t6
t8 = *(t7 + boffset);   // b[2]
t9 = t4 + t8;
*(fp + xoffset) = t9;   // x = …
t10 = *(fp + xoffset); // x
t12 = t10 - 5;
t13 = *(fp + ioffset); // i
t14 = t13 << 2;
t15 = fp + t14;
*(t15 + coffset) = t12; // c[i] := …
```

An example

```
x = a[i] + b[2];
c[i] = x - 5;
```

```
t1 = *(fp + ioffset);  // i
t2 = t1 << 2;
t3 = fp + t2;
t4 = *(t3 + aoffset);  // a[i]
t7 = boffset + 8;  // was fp + 8
t8 = *(t7 + fp);  // b[2] (was t7 + boffset)
t9 = t4 + t8;
*(fp + xoffset) = t9;  // x = …
t10 = *(fp + xoffset); // x
t12 = t10 - 5;
t13 = *(fp + ioffset); // i
t14 = t13 << 2;
t15 = fp + t14;
*(t15 + coffset) = t12; // c[i] := …
```

Arithmetic identities: + is commutative & associative. `boffset` is typically a known, compile-time constant (say -32), so this enables…

An example

```
x = a[i] + b[2];
c[i] = x - 5;
```

… more constant folding, which in turn enables …

```
t1 = *(fp + ioffset);  // i
t2 = t1 << 2;
t3 = fp + t2;
t4 = *(t3 + aoffset);  // a[i]
t7 = -24;         // was boffset (-32) + 8
t8 = *(t7 + fp);       // b[2]
t9 = t4 + t8;
*(fp + xoffset) = t9;  // x = …
t10 = *(fp + xoffset); // x
t12 = t10 - 5;
t13 = *(fp + ioffset); // i
t14 = t13 << 2;
t15 = fp + t14;
*(t15 + coffset) = t12; // c[i] := …
```

An example

```
x = a[i] + b[2];
c[i] = x - 5;
```

More constant propagation and dead store elimination

```
t1 = *(fp + ioffset);   // i
t2 = t1 << 2;
t3 = fp + t2;
t4 = *(t3 + aoffset);   // a[i]
~~t7 = -24;~~
t8 = *(fp - 24);  // b[2]   (was t7+fp)
t9 = t4 + t8;
*(fp + xoffset) = t9;   // x = …
t10 = *(fp + xoffset); // x
t12 = t10 - 5;
t13 = *(fp + ioffset); // i
t14 = t13 << 2;
t15 = fp + t14;
*(t15 + coffset) = t12; // c[i] := …
```

An example

```
x = a[i] + b[2];
c[i] = x - 5;
```

Common subexpression elimination – no need to compute *(fp+ioffset) again if we know it won't change

```
t1 = *(fp + ioffset);   // i
t2 = t1 << 2;
t3 = fp + t2;
t4 = *(t3 + aoffset);   // a[i]
t8 = *(fp - 24);        // b[2]
t9 = t4 + t8;
*(fp + xoffset) = t9;   // x = …
t10 = *(fp + xoffset); // x
t12 = t10 – 5;
t13 = t1;          // i   (was *(fp + ioffset))
t14 = t13 << 2;
t15 = fp + t14;
*(t15 + coffset) = t12; // c[i] := …
```

An example

```
x = a[i] + b[2];
c[i] = x - 5;
```

Copy propagation: replace assignment targets with their values (e.g., replace t13 with t1)

```
t1 = *(fp + ioffset);   // i
t2 = t1 << 2;
t3 = fp + t2;
t4 = *(t3 + aoffset);   // a[i]
t8 = *(fp - 24);        // b[2]
t9 = t4 + t8;
*(fp + xoffset) = t9;   // x = …
t10 = t9;          // x (was *(fp + xoffset))
t12 = t10 - 5;
t13 = t1;               // i
t14 = t1 << 2;   // was t13 << 2
t15 = fp + t14;
*(t15 + coffset) = t12; // c[i] := …
```

An example

```
x = a[i] + b[2];
c[i] = x - 5;
```

Common subexpression elimination

```
t1 = *(fp + ioffset);  // i
t2 = t1 << 2;
t3 = fp + t2;
t4 = *(t3 + aoffset);  // a[i]
t8 = *(fp - 24);       // b[2]
t9 = t4 + t8;
*(fp + xoffset) = t9;  // x = …
t10 = t9;              // x
t12 = t10 - 5;
t13 = t1;              // i
t14 = t2;       // was t1 << 2
t15 = fp + t14;
*(t15 + coffset) = t12; // c[i] := …
```

An example

```
x = a[i] + b[2];
c[i] = x - 5;
```

More copy propagation

```
t1 = *(fp + ioffset);   // i
t2 = t1 << 2;
t3 = fp + t2;
t4 = *(t3 + aoffset);   // a[i]
t8 = *(fp - 24);        // b[2]
t9 = t4 + t8;
*(fp + xoffset) = t9;   // x = …
t10 = t9;               // x
t12 = t9 - 5;     // was t10 - 5
t13 = t1;               // i
t14 = t2;
t15 = fp + t14;
*(t15 + coffset) = t12; // c[i] := …
```

An example

```
x = a[i] + b[2];
c[i] = x - 5;
```

More copy propagation

```
t1 = *(fp + ioffset);   // i
t2 = t1 << 2;
t3 = fp + t2;
t4 = *(t3 + aoffset);   // a[i]
t8 = *(fp - 24);        // b[2]
t9 = t4 + t8;
*(fp + xoffset) = t9;   // x = …
t10 = t9;               // x
t12 = t9 - 5;
t13 = t1;               // i
t14 = t2;
t15 = fp + t2;           // was fp + t14
*(t15 + coffset) = t12; // c[i] := …
```

An example

```
x = a[i] + b[2];
c[i] = x - 5;
```

```
t1 = *(fp + ioffset);  // i
t2 = t1 << 2;
t3 = fp + t2;
t4 = *(t3 + aoffset);  // a[i]
t8 = *(fp - 24);       // b[2]
t9 = t4 + t8;
*(fp + xoffset) = t9;  // x = …
t10 = t9;              // x
t12 = t9 – 5;
t13 = t1;              // i
t14 = t2;
t15 = t3               // was fp + t2
*(t3 + coffset) = t12; // was *(t15 + ...)
```

More common subexpression elimination and copy propagation

An example

```
x = a[i] + b[2];
c[i] = x - 5;
```

Dead assignment elimination

```
t1 = *(fp + ioffset);   // i
t2 = t1 << 2;
t3 = fp + t2;
t4 = *(t3 + aoffset);   // a[i]
t8 = *(fp - 24);        // b[2]
t9 = t4 + t8;
*(fp + xoffset) = t9;   // x = …
~~t10 = t9;             // x~~
t12 = t9 - 5;
~~t13 = t1;             // i~~
~~t14 = t2;~~
~~t15 = t3;~~
*(t3 + coffset) = t12;  // c[i] := …
```

An example

```
x = a[i] + b[2];
c[i] = x - 5;
```

```
t1 = *(fp + ioffset);   // i
t2 = t1 << 2;
t3 = fp + t2;
t4 = *(t3 + aoffset);   // a[i]
t8 = *(fp - 24);        // b[2]
t9 = t4 + t8;
*(fp + xoffset) = t9;   // x = …
t12 = t9 - 5;
*(t3 + coffset) = t12; // c[i] := …
```

- Final: 3 loads (i, a[i], b[2]), 2 stores (x, c[i]), 4 register-only moves, 8 +/-, 1 shift
- Original: 5 loads, 2 stores, 10 register-only moves, 12 +/-, 3 *

- Optimizer note: we usually leave assignment of actual registers to later stage of the compiler and assume as many "pseudo registers" as we need here

Kinds of optimizations

- peephole: look at adjacent instructions
- local: look at individual *basic blocks*
  - straight-line sequence of statements
- intraprocedural: look at whole procedure
  - Commonly called “global”
- interprocedural: look across procedures
  - “whole program” analysis
  - gcc’s “link time optimization” is a version of this
- Larger scope => usually more effective optimization when it can be done, but more cost and complexity
  - Analysis is often less precise because of more possibilities

Peephole Optimization

- After target code generation, look at adjacent instructions (a “peephole” on the code stream)
  - try to replace adjacent instructions with something faster

`movq %r9,16(%rsp)` `movq 16(%rsp),%r12`	`movq %r9,16(%rsp)` `movq %r9,%r12`

  - Jump chaining can also be considered a form of peephole optimization (removing jump to jump)

More Examples

`subq $8,%rax`
`movq %r2,0(%rax)`
`# %rax modified`
`# before next read`
	`movq %r2,-8(%rax)`

`movq 16(%rsp),%rax`
`addq $1,%rax`
`movq %rax,16(%rsp)`
`# %rax modified`
`# before next read`
	`incq 16(%rsp)`

- One way to do complex instruction selection

Algebraic Simplification

- “constant folding”, “strength reduction”
  - `z = 3 + 4;` → `z = 7`
  - `z = x + 0;` → `z = x`
  - `z = x * 1;` → `z = x`
  - `z = x * 2;` → `z = x << 1  or z = x + x`
  - `z = x * 8;` → `z = x << 3`
  - `z = x / 8;` → `z = x >> 3 (only if know x>=0)`
  - `z = (x + y) - y;` → `z = x (maybe; not doubles, might change int overflow)`
- Can be done at many levels from peephole on up
- Why do these examples happen?
  - Often created during conversion to lower-level IR, by other optimizations, code gen, etc.

Local Optimizations

- Analysis and optimizations within a basic block
- *Basic block*: straight-line sequence of statements
  - no control flow into or out of middle of sequence
- Better than peephole
- Not too hard to implement with reasonable IR

- Machine-independent, if done on IR

Local Constant Propagation

- If variable assigned a constant, replace downstream uses of the variable with the constant (until variable reassigned)
- Can enable more constant folding
  - Code; unoptimized intermediate code:

```
count = 10;
...   // count not changed
x = count * 5;
y = x ^ 3;
x = 7;
```

```
count = 10;
t1 = count;
t2 = 5;
t3 = t1 * t2;
x = t3;
t4 = x;
t5 = 3;
t6 = exp(t4,t5);
y = t6;
x = 7
```

Local Constant Propagation

- If variable assigned a constant, replace downstream uses of the variable with constant (until variable reassigned)
- Can enable more constant folding
  - Code; constant propagation:

```
count = 10;
...  // count not changed
x = count * 5;
y = x ^ 3;
x = 7;
```

```
count = 10;
t1 = 10;       // cp count
t2 = 5;
t3 = 10 * t2;  // cp t1
x = t3;
t4 = x;
t5 = 3;
t6 = exp(t4,3);  // cp t5
y = t6;
x = 7
```

Local Constant Propagation

- If variable assigned a constant, replace downstream uses of the variable with constant (until variable reassigned)
- Can enable more constant folding
  - Code; constant folding:

```
count = 10;
...   // count not changed
x = count * 5;
y = x ^ 3;
x = 7;
```

```
count = 10;
t1 = 10;
t2 = 5;
t3 = 50;          // 10*t2
x = t3;
t4 = x;
t5 = 3;
t6 = exp(t4,3);
y = t6;
x = 7;
```

Local Constant Propagation

- If variable assigned a constant, replace downstream uses of the variable with constant (until variable reassigned)
- Can enable more constant folding
  - Code; repropagated intermediate code

```
count = 10;
...   // count not changed
x = count * 5;
y = x ^ 3;
x = 7;
```

```
count = 10;
t1 = 10;
t2 = 5;
t3 = 50;
x = 50;      // cp t3
t4 = 50;     // cp x
t5 = 3;
t6 = exp(50,3); // cp t4
y = t6;
x = 7;
```

Local Constant Propagation

- If variable assigned a constant, replace downstream uses of the variable with constant (until variable reassigned)
- Can enable more constant folding
  - Code; refold intermediate code

```
count = 10;
...   // count not changed
x = count * 5;
y = x ^ 3;
x = 7;
```

```
count = 10;
t1 = 10;
t2 = 5;
t3 = 50;
x = 50;
t4 = 50;
t5 = 3;
t6 = 125000; // cf 50^3
y = t6;
x = 7;
```

Local Constant Propagation

- If variable assigned a constant, replace downstream uses of the variable with constant (until variable reassigned)
- Can enable more constant folding
  - Code; repropagated intermediate code

```
count = 10;
...  // count not changed
x = count * 5;
y = x ^ 3;
x = 7;
```

```
count = 10;
t1 = 10;
t2 = 5;
t3 = 50;
x = 50;
t4 = 50;
t5 = 3;
t6 = 125000;
y = 125000;  // cp t6
x = 7;
```

Local Dead Assignment Elimination

- If l.h.s. of assignment never referenced again before being overwritten, then can delete assignment
  - Why would this happen?
    Clean-up after previous optimizations, often

```
count = 10;
...   // count not changed
x = count * 5;
y = x ^ 3;
x = 7;
```

```
count = 10;
t1 = 10;
t2 = 5;
t3 = 50;
x = 50;
t4 = 50;
t5 = 3;
t6 = 125000;
y = 125000;
x = 7;
```

Local Dead Assignment Elimination

- If l.h.s. of assignment never referenced again before being overwritten, then can delete assignment
  - Why would this happen?
    Clean-up after previous optimizations, often

```
count = 10;
...   // count not changed
x = count * 5;
y = x ^ 3;
x = 7;
```

```
count = 10;
~~t1 = 10;~~
~~t2 = 5;~~
~~t3 = 50;~~
~~x = 50;~~
~~t4 = 50;~~
~~t5 = 3;~~
~~t6 = 125000;~~
y = 125000;
x = 7;
```

Can't delete if x=50 potentially visible, e.g., after exception

Local Common Subexpression Elimination

- Look for repetitions of the same computation. Eliminate them if result won't have changed and no side effects
  - Avoid repeated calculation and eliminates redundant loads
- Idea: walk through basic block keeping track of available expressions

```
... a[i] + b[i] ...
```

```
t1 = *(fp + ioffset);
t2 = t1 * 4;
t3 = fp + t2;
t4 = *(t3 + aoffset);
t5 = *(fp + ioffset);
t6 = t5 * 4;
t7 = fp + t6;
t8 = *(t7 + boffset);
t9 = t4 + t8;
```

Local Common Subexpression Elimination

- Look for repetitions of the same computation. Eliminate them if result won't have changed and no side effects
  - Avoid repeated calculation and eliminates redundant loads
- Idea: walk through basic block keeping track of available expressions

```
... a[i] + b[i] ...
```

```
t1 = *(fp + ioffset);
t2 = t1 * 4;
t3 = fp + t2;
t4 = *(t3 + aoffset);
t5 = t1;    // CSE
t6 = t5 * 4;
t7 = fp + t6;
t8 = *(t7 + boffset);
t9 = t4 + t8;
```

Local Common Subexpression Elimination

- Look for repetitions of the same computation. Eliminate them if result won't have changed and no side effects
  - Avoid repeated calculation and eliminates redundant loads
- Idea: walk through basic block keeping track of available expressions

```
... a[i] + b[i] ...
```

```
t1 = *(fp + ioffset);
t2 = t1 * 4;
t3 = fp + t2;
t4 = *(t3 + aoffset);
t5 = t1;
t6 = t1 * 4;   // CP
t7 = fp + t6;
t8 = *(t7 + boffset);
t9 = t4 + t8;
```

Local Common Subexpression Elimination

- Look for repetitions of the same computation. Eliminate them if result won't have changed and no side effects
  - Avoid repeated calculation and eliminates redundant loads
- Idea: walk through basic block keeping track of available expressions

```
... a[i] + b[i] ...
```

```
t1 = *(fp + ioffset);
t2 = t1 * 4;
t3 = fp + t2;
t4 = *(t3 + aoffset);
t5 = t1;
t6 = t2;        // CSE
t7 = fp + t2; // CP
t8 = *(t7 + boffset);
t9 = t4 + t8;
```

Local Common Subexpression Elimination

- Look for repetitions of the same computation. Eliminate them if result won’t have changed and no side effects
  - Avoid repeated calculation and eliminates redundant loads
- Idea: walk through basic block keeping track of available expressions

```
... a[i] + b[i] ...
```

```
t1 = *(fp + ioffset);
t2 = t1 * 4;
t3 = fp + t2;
t4 = *(t3 + aoffset);
t5 = t1;
t6 = t2;
t7 = t3;  // CSE
t8 = *(t3 + boffset); //CP
t9 = t4 + t8;
```

Local Common Subexpression Elimination

- Look for repetitions of the same computation. Eliminate them if result won't have changed and no side effects
  - Avoid repeated calculation and eliminates redundant loads
- Idea: walk through basic block keeping track of available expressions

```
... a[i] + b[i] ...
```

```
t1 = *(fp + ioffset);
t2 = t1 * 4;
t3 = fp + t2;
t4 = *(t3 + aoffset);
~~t5 = t1;~~   // DAE
~~t6 = t2;~~   // DAE
~~t7 = t3;~~   // DAE
t8 = *(t3 + boffset);
t9 = t4 + t8;
```

Intraprocedural optimizations

- Enlarge scope of analysis to whole procedure
  - more opportunities for optimization
  - have to deal with branches, merges, and loops
- Can do constant propagation, common subexpression elimination, etc. at “global” level
- Can do new things, e.g. loop optimizations
- Optimizing compilers often work at this level (-O2)

Code Motion

- Goal: move loop-invariant calculations out of loops
- Can do at source level or at intermediate code level

```
for (i = 0; i < 10; i = i+1) {
  a[i] = a[i] + b[j];
  z = z + 10000;
}
```

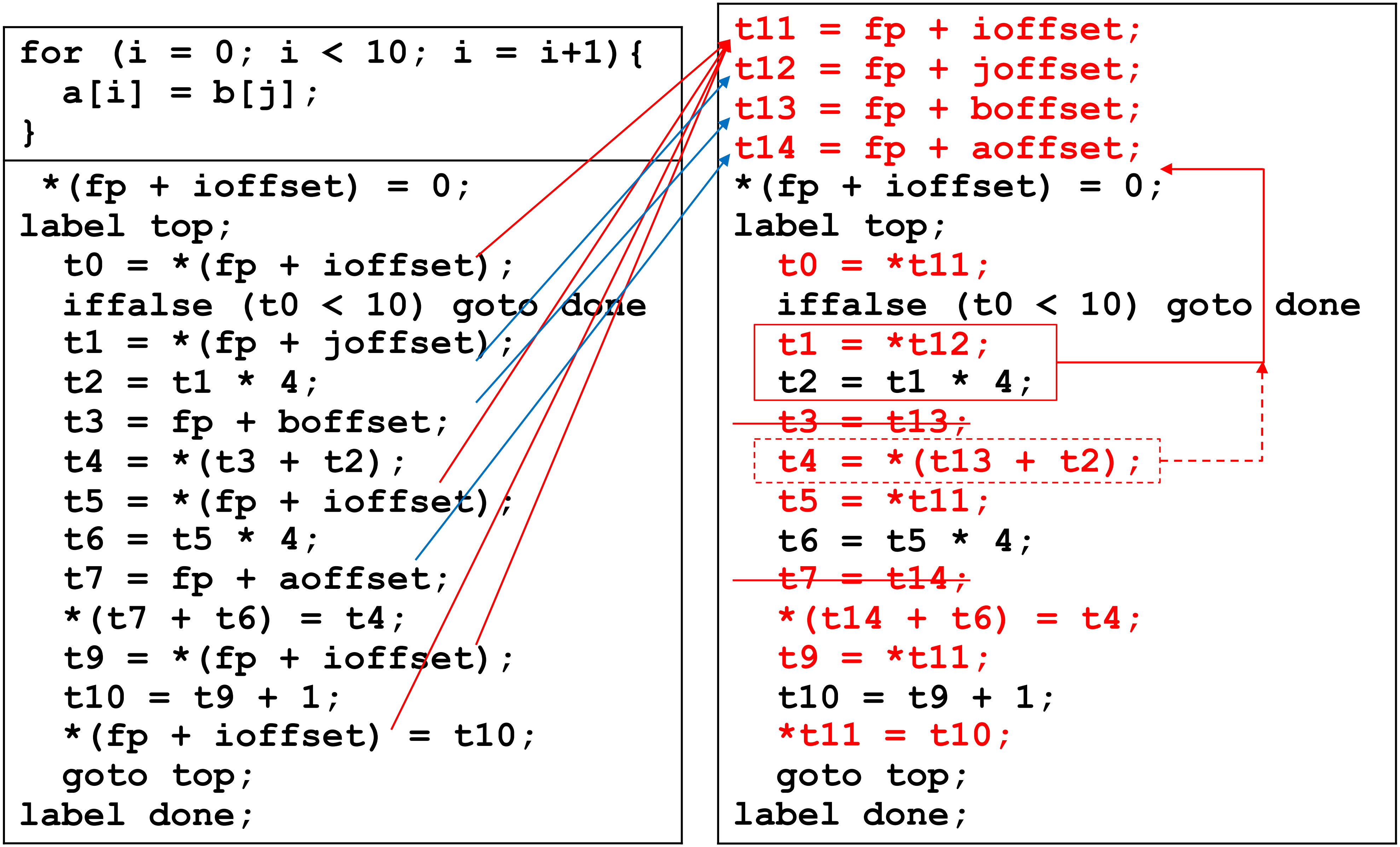
```
t1 = b[j];
t2 = 10000;
for (i = 0; i < 10; i = i+1) {
  a[i] = a[i] + t1;
  z = z + t2;
}
```

Code Motion at IL

```
for (i = 0; i < 10; i = i+1) {
  a[i] = b[j];
}
```

```
 *(fp + ioffset) = 0;
label top;
  t0 = *(fp + ioffset);
  iffalse (t0 < 10) goto done;
  t1 = *(fp + joffset);
  t2 = t1 * 4;
  t3 = fp + t2;
  t4 = *(t3 + boffset);
  t5 = *(fp + ioffset);
  t6 = t5 * 4;
  t7 = fp + t6;
  *(t7 + aoffset) = t4;
  t9 = *(fp + ioffset);
  t10 = t9 + 1;
  *(fp + ioffset) = t10;
  goto top;
label done;
```

Code Motion at IL



```
for (i = 0; i < 10; i = i+1){
  a[i] = b[j];
}
```

```
 *(fp + ioffset) = 0;
label top;
  t0 = *(fp + ioffset);
  iffalse (t0 < 10) goto done
  t1 = *(fp + joffset);
  t2 = t1 * 4;
  t3 = fp + boffset;
  t4 = *(t3 + t2);
  t5 = *(fp + ioffset);
  t6 = t5 * 4;
  t7 = fp + aoffset;
  *(t7 + t6) = t4;
  t9 = *(fp + ioffset);
  t10 = t9 + 1;
  *(fp + ioffset) = t10;
  goto top;
label done;
```

```
t11 = fp + ioffset;
t12 = fp + joffset;
t13 = fp + boffset;
t14 = fp + aoffset;
*(fp + ioffset) = 0;
label top;
  t0 = *t11;
  iffalse (t0 < 10) goto done
  t1 = *t12;
  t2 = t1 * 4;
  ~~t3 = t13;~~
  t4 = *(t13 + t2);
  t5 = *t11;
  t6 = t5 * 4;
  ~~t7 = t14;~~
  *(t14 + t6) = t4;
  t9 = *t11;
  t10 = t9 + 1;
  *t11 = t10;
  goto top;
label done;
```

Loop Induction Variable Elimination

- Common special case of loop-based strength reduction
- For-loop index is *induction variable*
  - incremented each time around loop
  - offsets & pointers calculated from it
- If used only to index arrays, rewrite with pointers
  - compute initial offsets/pointers before loop
  - increment offsets/pointers each time around loop
  - no expensive scaling in loop
  - then do loop-invariant code motion

```
for (i = 0; i < 10; i = i+1){
  a[i] = a[i] + x;
}
```

```
for (p = &a[0]; p < &a[10]; p = p+4){
  *p = *p + x;
}
```

Interprocedural Optimization

- Expand scope of analysis to procedures calling each other
- Can do local & intraprocedural optimizations at larger scope
- Can do new optimizations, e.g. inlining

Inlining: replace call with body

- Replace procedure call with body of callee

Especially important for object getter/setter methods, to avoid overhead for these frequent but trivial procedure calls

- Source:

```
final double pi = 3.1415927;
double circle_area(double radius) {
   return pi * (radius * radius);
}
...
double r = 5.0;
...
double a = circle_area(r);
```

- After inlining:

```
...
double r = 5.0;
...
double a = pi * r * r;
```

Actually, closer to this:

```
double t = r
double a = pi * t * t
```

And worry about scopes, etc.

- (Then what? Constant propagation/folding)

Data Structures for Optimizations

- Need to represent control and data flow
- Control flow graph (CFG) captures flow of control
  - nodes are IL statements, or whole basic blocks
  - edges represent (all possible) control flow
  - node with multiple successors = branch/switch
  - node with multiple predecessors = merge
  - cycle in graph = loop
- Data flow graph (DFG) captures flow of data, e.g. def/use chains:
  - nodes are def(inition)s and uses
  - edge from def to use
  - a def can reach multiple uses
  - a use can have multiple reaching defs (different control flow paths, possible aliasing, etc.)
- SSA: another widely used way of linking defs and uses

Analysis and Transformation

- Each optimization is made up of
  - some number of analyses
  - followed by a transformation
- Analyze CFG and/or DFG by propagating info forward or backward along CFG and/or DFG edges
  - merges in graph require combining info
  - loops in graph require *iterative approximation*
- Perform (improving) transformations based on info computed
- Analysis must be conservative/safe/sound so that transformations preserve program behavior

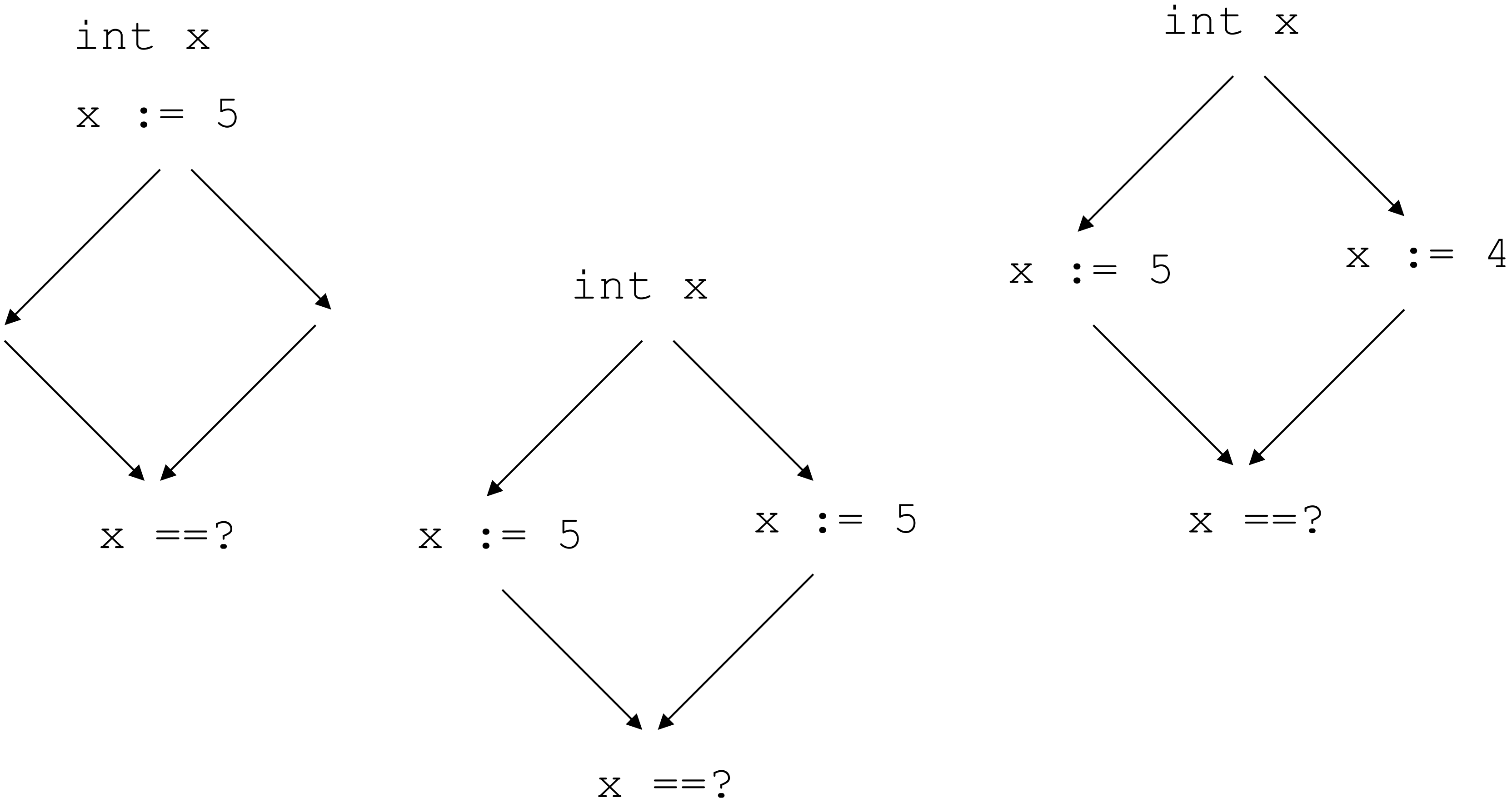
Example: Constant Propagation, Folding

- Can use either the CFG or the DFG
- CFG analysis info: table mapping each variable in scope to one of:
  - a particular constant
  - NonConstant
  - Undefined
- Transformation at each instruction:
  - If an assignment of a constant to a variable, set variable as a constant with known value
  - If reference to a variable that the table maps to a constant, then replace with that constant (constant propagation)
  - if r.h.s. expression involves only constants, and has no side-effects, then perform operation at compile-time and replace r.h.s. with constant result (constant folding)
- For best analysis, do constant folding as part of analysis, to learn all constants in one pass

Merging data flow analysis info

- Constraint: merge results must be sound
  - if something is believed true after the merge, then it must be true no matter which path we took into the merge
  - only things true along all predecessors are true after the merge
- To merge two maps of constant information, build map by merging corresponding variable information
- To merge information about two variables:
  - if one is Undefined, keep the other
  - if both are the same constant, keep that constant
  - otherwise, degenerate to NonConstant (NC)

Example Merges

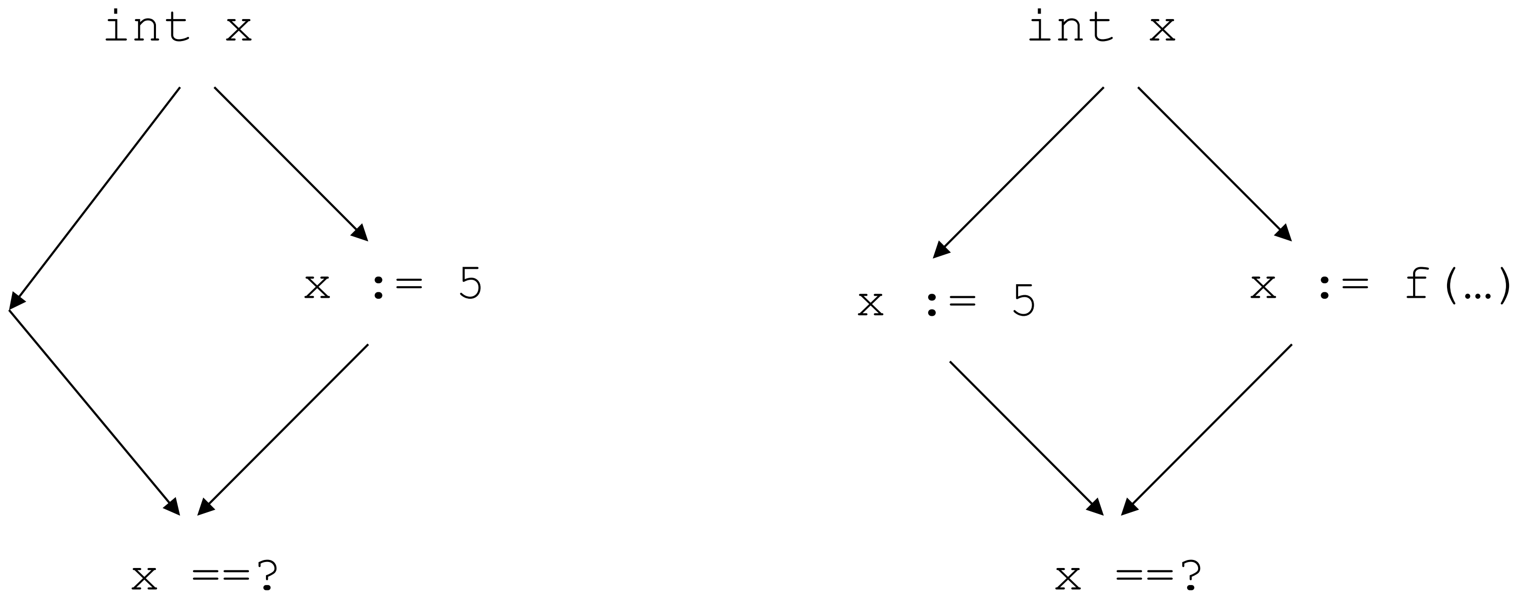


```
int x
x := 5
x ==?
```

```
int x
x := 5
x := 5
x ==?
```

```
int x
x := 5
x := 4
x ==?
```

Example Merges



`int x`

`x := 5`

`x ==?`

`int x`

`x := 5`

`x := f(…)`

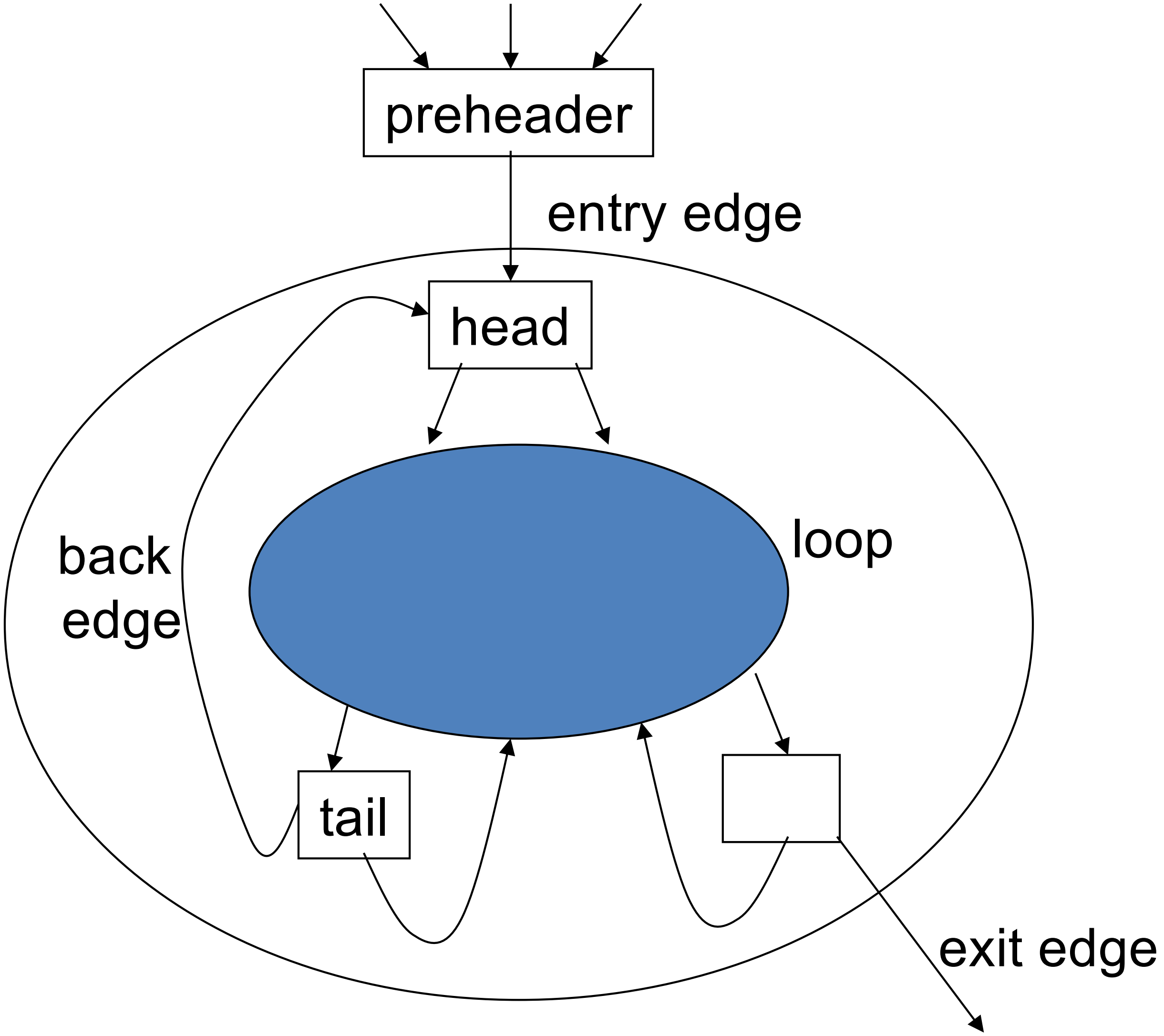
`x ==?`

How to analyze loops

```
i = 0;
x = 10;
y = 20;
while (...) {
  // what’s true here?
  ...
  i = i + 1;
  y = 30;
}
// what’s true here?
... x ... i ... y ...
```

- Safe but imprecise: forget everything when we enter or exit a loop
- Precise but unsafe: keep everything when we enter or exit a loop
- Can we do better?

Loop Terminology



Optimistic Iterative Analysis

- Initially assume information at loop head is same as information at loop entry
- Then analyze loop body, computing information at back edge
- Merge information at loop back edge and loop entry
- Test if merged information is same as original assumption
  - If so, then we're done
  - If not, then replace previous assumption with merged information,
  - and go back to analysis of loop body

Example

```
i = 0;
x = 10;
y = 20;
while (...) {
   // what's true here?
   ...
   i = i + 1;
   y = 30; }
// what's true here?
... x ... i ... y ...
```

i = 0, x = 10, y = 20

i = 1, x = 10, y = 30

Example

```
i = 0;
x = 10;
y = 20;
while (...) {
   // what’s true here?
   ...
   i = i + 1;
   y = 30; }
// what’s true here?
... x ... i ... y ...
```

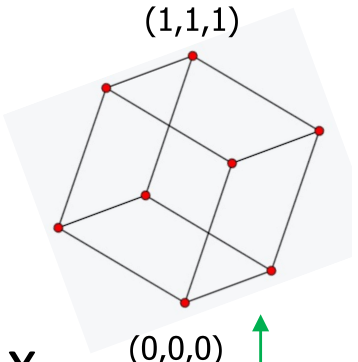
i = NC, x = 10, y = NC

i = NC, x = 10, y = NC

Why does this work?

- Why are the results always conservative?
- Because if the algorithm stops, then
  - the loop head info is at least as conservative as both the loop entry info and the loop back edge info
  - the analysis within the loop body is conservative, given the assumption that the loop head info is conservative
- Will it terminate?
  - Yes, if there are only a finite number of times we can merge information before reaching worst-case info (e.g., NonConstant / NC in this example)

Termination – more generally



- Suppose alg has a "state" vector x = (x_1,x_2,…,x_n), each x_i from a *finite*, ordered set, say {0,1} or {1,2,3}
- If each state transition (iteration of an alg, such as prev few slides) allowed, say, x_i to go up while x_j goes down, then ∞ iteration is possible: (0,1) → (1,0) → (0,1) → …
- *BUT*, if alg ensures that, at each iteration, old-x_i ≤ new-x_i, then termination is certain: You can only increase x_i a *finite* number of times before you hit the top value
- E.g., if $x_i \in \{0,1\}$, x = (x_1,x_2,…,x_n) are corners of an n-cube; at worst, alg walks from (0,0,…,0) to (1,1,…,1) in ≤ n steps
- Math Jargon: such a structure is typically called a "lattice".

More analyses

- Alias analysis
  - Detect when different references may or must refer to the same memory locations
- Escape analysis
  - Pointers that are live on exit from procedures
  - Pointed-to data may “escape” to other procedures or threads
- Dependence analysis
  - Determining which references depend on which other references
  - One application: analyze array subscripts that depend on loop induction variables to determine which loop iterations depend on each other
    - Key analysis for loop parallelization/vectorization

Summary

- Optimizations organized as collections of passes, each rewriting IL in place into (hopefully) better version
- Each pass does analysis to determine what is possible, followed by transformation(s) that (hopefully) improve the program
  - Sometimes "analysis-only" passes are helpful
  - Often redo analysis/transformations again to take advantage of possibilities revealed by previous changes
- Presence of optimizations makes other parts of compiler (e.g. intermediate and target code generation) easier to write since they can defer to optimization pass to improve/clean up simple-and-easy-to-generate-correct-but-not-clever code