CSE 401/M501 – Compilers

Survey of Code Optimizations

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Administrivia

- Semantics/type checking due Thursday night
  - Be sure to review MiniJava project description and semantics project assignment when you think you're "done"
  - And check your work (ant clean, then ant, etc.)
- CSE M 501 "project extras" requirements – if your group hasn't done so yet, please figure out what you plan to do and discuss with instructor soon (send email to cse401-staff outlining what you have in mind to start)

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

Why optimize code?

Many possible goals – not all compatible

- Run faster
- Use less memory for program code
- Use less memory during execution
- Use less power
- Run on smaller/cheaper machines (particularly for embedded systems, phones…)
- etc.
- Compiler engineering – separation of concerns: generate correct code with simple, clean algorithms, then improve it in separate optimization phases
  - If you already have optimization passes, don't duplicate work

Goals and constraints

- Want to make code “better” (faster, smaller, etc. depending on our goals), but ….
- Must not change the externally visible behavior of the program guaranteed by the language definition
  - Input/output/error/exception behavior must be the same
  - Runs faster? Observable, but usually what we want, but sometimes a security issue
- Some optimizations are always a good idea, but some are usually a good idea so we do them even when they don’t improve things in (we hope) unusual cases
- “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” t*n* as we need here; using a *new* t*n* 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;
```

Constant propagation: replace variables with known constant values

```
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] := …
```

An example

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

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

```
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] := …
```

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]
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] := …
```

Constant folding: statically compute operations with known constant values

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;
```

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

```
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] := …
```

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;
```

```
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] := …
```

More constant propagation and dead store elimination

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] := …
```

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

- 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

Optimizations in the example

- *strength reduction*
- *constant propagation*
- *dead code elimination*
- *constant folding*
- *constant propagation*
- *dead code elimination*
- *algebraic simplification*
- *constant propagation*
- *constant folding*
- *dead code elimination*
- *common subexpr. elim.*
- *copy propagation*
- *common subexpr. elim.*
- *copy propagation*
- *common subexpr. elim.*
- *copy propagation*
- *dead code elimination*

- Unlike in our example, compilers tend to work on code in *passes* that go over a large amount of code, rather than make a random bunch of individual changes.
- Some optimizations are needed to expose the opportunity for other optimizations. Some optimizations change code and hide other possibilities. What order should we choose?
  - This is known as the *phase ordering* problem

llvm –O2 optimization passes

targetlibinfo
tti
no-aa
tbaa
scoped-noalias
assumption-
  cache-tracker
basicaa
ipsccp
globalopt
deadargelim
domtree
instcombine
simplifycfg
basiccg
prune-eh
inline-cost
inline
functionattrs
domtree
sroa
early-cse
lazy-value-info
jump-threading
correlated-
  propagation
simplifycfg
domtree
instcombine

tailcallelim
simplifycfg
reassociate
domtree
loops
loop-simplify
lcssa
loop-rotate
licm
loop-unswitch
instcombine
scalar-evolution
loop-simplify
lcssa
indvars
loop-idiom
loop-deletion
loop-unroll
mldst-motion
domtree
memdep
gvn
memdep
memcpyopt
sccp
domtree
bdce
instcombine
lazy-value-info

jump-threading
correlated-
propagation
domtree
memdep
dse
loops
loop-simplify
lcssa
licm
adce
simplifycfg
domtree
instcombine
barrier
float2int
domtree
loops
loop-simplify
lcssa
loop-rotate
branch-prob
block-freq
scalar-evolution
loop-accesses
loop-vectorize
instcombine
scalar-evolution
slp-vectorizer

simplifycfg
domtree
instcombine
loops
loop-simplify
lcssa
scalar-evolution
loop-unroll
instcombine
loop-simplify
lcssa
licm
scalar-evolution
alignment-from-
  assumptions strip-
dead-
  prototypes
elim-avail-
  extern
globaldce
constmerge
verify

Scope 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 = 10;`
`...  // count not changed`	`t1 = 10;`
`x = count * 5;`	`t2 = 5;`
`y = x ^ 3;`	`t3 = 50;`
`x = 7;`	`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 = 10;`
`...  // count not changed`	~~`t1 = 10;`~~
`x = count * 5;`	~~`t2 = 5;`~~
`y = x ^ 3;`	~~`t3 = 50;`~~
`x = 7;`	~~`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

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- 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
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	`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
  - Code inside loops often has biggest impact on performance, so improvements here are often the most important
- 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
- 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;
```

- (Then what? Constant propagation/folding)

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

Actually, closer to this:

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

And worry about scopes, etc.

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

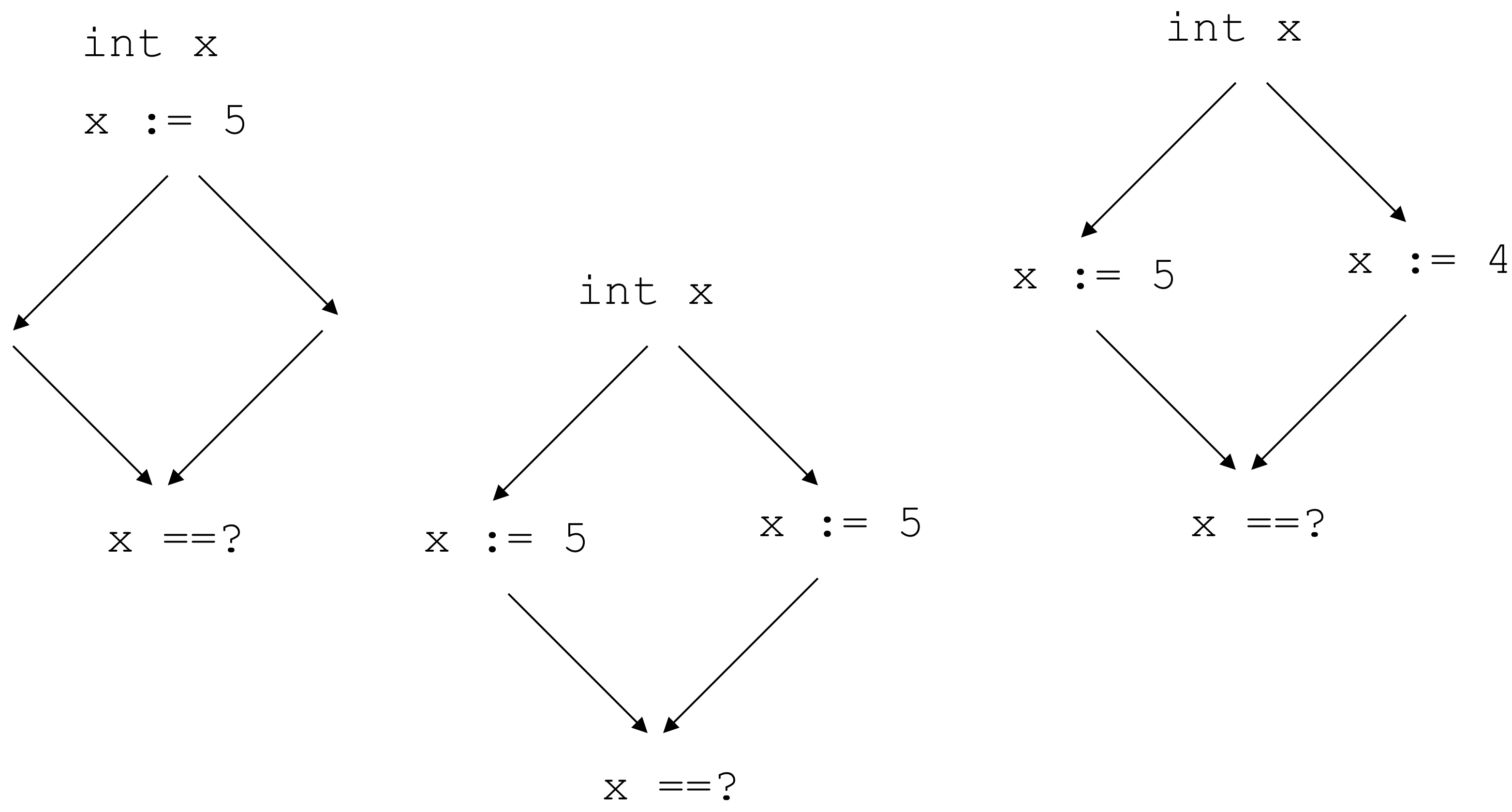
Example: Constant Propagation, Folding

- 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

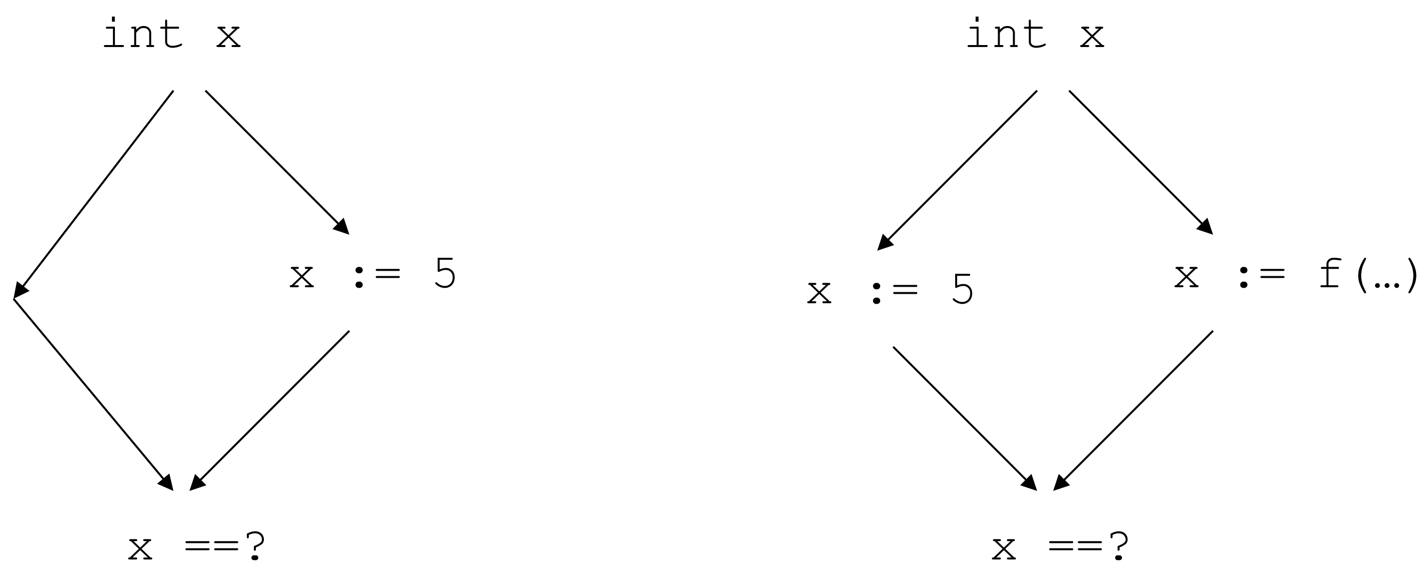
Merging data flow analysis info

- 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



Example Merges

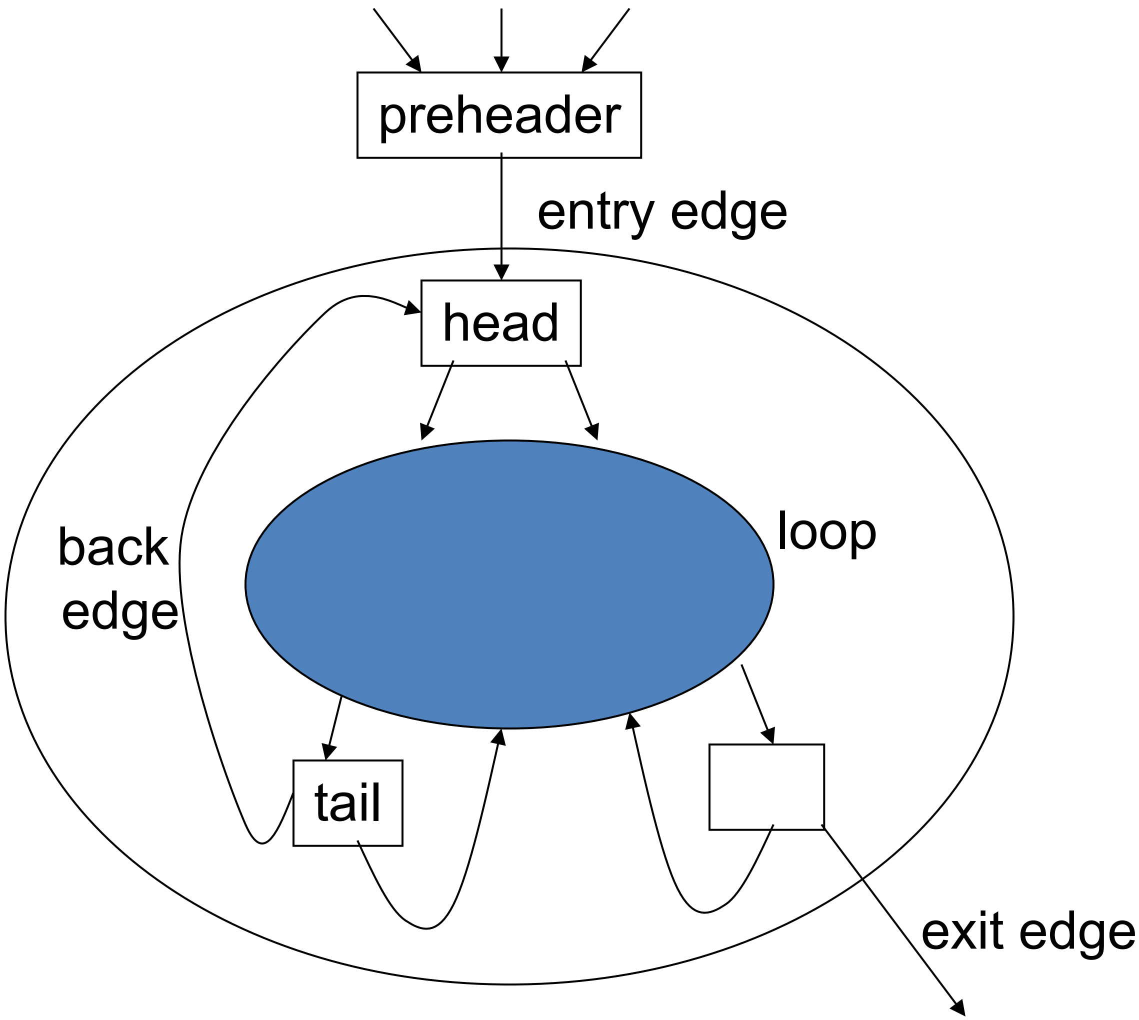


How to analyze loops

```
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 ...
```

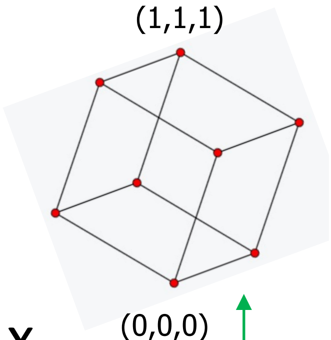
i = NC, x = 10, y = NC

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 $x = (x_1,x_2,\ldots,x_n)$, 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-$x_i \leq$ 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 $x_i \in \{0,1\}$, $x = (x_1,x_2,\ldots,x_n)$ 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