Optimization of C Programs

C Programming and Software Tools

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with material from R. Bryant and D. O'Halloran "Computer Systems: A Programmer's Perspective" and Jon Louis Bentley "Writing Efficient Programs"

Optimization

- Performance depends on...
  1. algorithm / data structure choices
  2. coding style
  3. compiler + options
  4. programming language (C is a good choice ☺)

Compilers

- Most compilers offer a variety of optimization choices
- **gcc**: **-O** or **–O1** or **–O2** or **–O3** (in order of increasing optimization)
- How much can you expect this to help?
- Does it ever hurt?

Compilers... (cont'd)

All the gcc choices(!) :

```
-falign-functions=n -falign-jumps=n -falign-labels=n -falign-loops=n -fbounds-
check -fmudflap -fmudflapth -fmudflapir -fbranch-probabilities -fprofile-values
-fvpt -fbranch-target-load-optimize -fbranch-target-load-optimize2 -fbtr-bb-
exclusive -fcaller-saves -fcprop-registers -fcse-follow-jumps -fcse-skip-blocks
-fcx-limited-range -fdata-sections -fdelayed-branch -fdelete-null-pointer-checks
-fearly-inlining -fexpensive-optimizations -ffast-math -ffloat-store -fforce-
addr -ffunction-sections -fgcse -fgcse-lm -fgcse-sm -fgcse-las -fgcse-after-
reload -floop-optimize -fcrossjumping -fif-conversion -fif-conversion2 -finline-
functions -finline-functions-called-once -finline-limit=n -fkeep-inline-
functions -fkeep-static-consts -fmerge-constants -fmerge-all-constants -fmodulo-
sched -fno-branch-count-reg -fno-default-inline -fno-defer-pop -floop-optimize2
-fmove-loop-invariants -fno-function-cse -fno-guess-branch-probability -fno-
inline -fno-math-errno -fno-peephole -fno-peephole2 -funsafe-math-optimizations
-funsafe-loop-optimizations -ffinite-math-only -fno-trapping-math -fno-zero-
initialized-in-bss -fomit-frame-pointer -foptimize-register-move -foptimize-
sibling-calls -fprefetch-loop-arrays -fprofile-generate -fprofile-use -fregmove
-frename-registers -freorder-blocks -freorder-blocks-and-partition -freorder-
functions -frerun-cse-after-loop -frerun-loop-opt -frounding-math -fschedule-
insns -fschedule-insns2 -fno-sched-interblock -fno-sched-spec -fsched-spec-load
-fsched-spec-load-dangerous -fsched-stalled-insns=n -fsched-stalled-insns-dep=n
-fsched2-use-superblocks -fsched2-use-traces -freschedule-modulo-scheduled-loops
-fsignaling-nans -fsingle-precision-constant -fstack-protector -fstack-
protector-all -fstrength-reduce -fstrict-aliasing -ftracer -fthread-jumps -
funroll-all-loops -funroll-loops -fpeel-loops -fsplit-ivs-in-unroller -
funswitch-loops -fvariable-expansion-in-unroller -ftree-pre -ftree-ccp -ftree-
dce -ftree-loop-optimize -ftree-loop-linear -ftree-loop-im -ftree-loop-ivcanon -
fivopts -ftree-dominator-opts -ftree-dse -ftree-copyrename -ftree-sink -ftree-ch
-ftree-sra -ftree-ter -ftree-lrs -ftree-fre -ftree-vectorize -ftree-vect-loop-
version -ftree-salias -fweb -ftree-copy-prop -ftree-store-ccp -ftree-store-copy-
prop -fwhole-program --param name=value -O -O0 -O1 -O2 -O3 -Os
```

Limitations on Optimizing

- Must not change program outputs or results
- May increase code length
- May decrease code readability
- C features that complicate optimization...
  - pointers
  - functions with side-effects

Code Profiling

- To speed up a program, you have to know where it spends the most time
- To measure execution time, use **`time`** utility
  `time ./program [command line args]`
- **`gprof`** : a tool for profiling program execution
  - counts number of times each function is called
  - + how much time spent in each function
  - Time values only useful for relative, not absolute, performance measurement

...Profiling (cont'd)

- To add cycle counting to your program, compile with **-pg** flag, e.g.,

```
gcc -pg pgm.c -o pgm
```

- When you run **pgm**, it produces normal output, but also generates a file called **gmon.out**
- Execute **gprof** after running the program, , e.g.,

```
gprof ./pgm
```


gprof Example

```
 %    cumulative   self
time     seconds seconds    calls
-----    ------- -------   ------
86.60       8.21    8.21        1  sort_words
 5.80       8.76    0.55   946596  lower1
 4.75       9.21    0.45   946596  find_ele_rec
 1.27       9.33    0.12   946596  h_add
```

- Shows number of calls and cumulative time for each function
- Where would you try to optimize the above program?

Code Motion

- move an expression evaluation outside of a loop (i.e., execute it fewer times)

Example

```
for (i = 0; i < n; i++)
  for (j = 0; j < n; j++)
    a[n*i + j] = f() * b[j];
```

Before optimization

```
k = f();
for (i = 0; i < n; i++) {
  int ni = n*i;
  for (j = 0; j < n; j++)
    a[ni + j] = k * b[j];
}
```

After optimization

Optimization?

```
/* Sum neighbors of i,j */
up =    val[(i-1)*n + j];
down =  val[(i+1)*n + j];
left =  val[i*n   + j-1];
right = val[i*n   + j+1];
sum = up + down + left + right;
```

Share (Reuse) Expression Results

- "Compute once, use twice", ex.:

```
/* Sum neighbors of i,j */
up =    val[(i-1)*n + j];
down =  val[(i+1)*n + j];
left =  val[i*n   + j-1];
right = val[i*n   + j+1];
sum = up + down + left + right;
```

Before optimization

3 different multiplications: `i*n, (i–1)*n, (i+1)*n`

1 multiplication: `i*n`

```
int inj = i*n + j;
up =    val[inj - n];
down =  val[inj + n];
left =  val[inj - 1];
right = val[inj + 1];
sum = up + down + left + right;
```

After optimization

Inlining Function Calls

- Replace a function call with equivalent inline

```
int
prod(int i, int j, int n, int b[n][n], int c[n][n])
{
  int sum = 0;
  for (k = 0; k < n; k++)
    sum += b[i][k] * c[k][j];
  return sum;
}

…
for (i = 0; i < n; i++)
  for (j = 0; j < n; j++)
    a[i][j] = prod(i, j, n, b, c);
```

Before optimization

M-I Optimization (cont'd)

After optimization

```
for (i = 0; i < n; i++)
  for (j = 0; j < n; j++) {
    sum = 0;
    for (k = 0; k < n; k++)
      sum += b[i][k] * c[k][j];
    a[i][j] = sum;
  }
```


Reordering Tests

- Place frequent **`case`** labels or **`if`** conditions first
  - reduces the average number of comparisons

```
if (height > 84)   /* extremely rare */
    f1();
else if (height > 72)    /* uncommon */
    f2();
else                 /* usually the case */
    f3();
```

Before optimization

Reordering Tests… (cont'd)

After optimization

```
if (height <= 72) /* usually the case */
    f3();
else if (height <= 84)    /* uncommon */
    f2();
else                  /* extremely rare */
    f1();
```


Pass Large Parameters by Reference

- Avoid passing large structs as arguments to functions.

```
struct mystruct {
    … many members, incl. array(s)…
} bigstruct;
…
int r = f(bigstruct);
…
int f(struct mystruct bigstruct) {
…
}
```

Before optimization

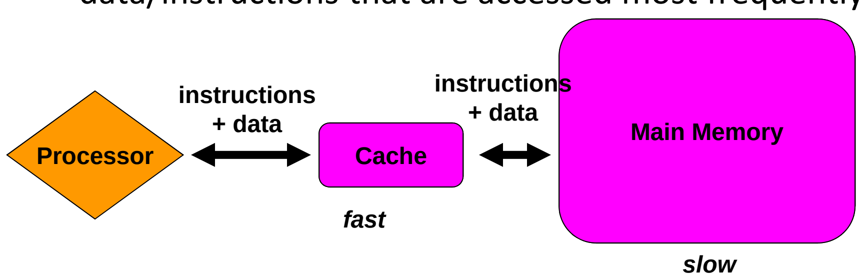
Pass Large … (cont'd)

After optimization

```
…
int r = f(&bigstruct);
…
int f(const struct mystruct *sp) {
…
}
```


Cache Optimization

- Caching speeds up memory access
  - store in the (small, expensive) cache the data/instructions that are accessed most frequently



The program design / data layout can improve cache performance substantially in some cases

Multi-Core

- Getting optimal performance from multi-core processors also requires careful attention to coding
  - current tools don't help that much

Recommendations from GNOME Project

- "If you want to optimize your program, the first step is to profile the program running with real life data and collect profiling information."
- "Do not write code that is hard to read and maintain if it is only to make the code faster."

Bentley's Fundamental Rules for Optimization

- Code Simplification
  - Fast programs are typically simple programs
- Problem Simplification
  - Example: simplify loop by moving some work outside of the loop
- Relentless Suspicion
  - Question every part of the data structure and algorithm bottleneck areas
- Early Binding
  - Do some work as early as possible and only once

Test!!!

- Optimizations should NEVER change functionality
  - Test your program to ensure no regression in behavior!!!
  - Test after each optimization