Lecture 24 — Profiling

Patrick Lam
p.lam@ece.uwaterloo.ca

Department of Electrical and Computer Engineering
University of Waterloo

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Part I

Profiling

Remember the Initial Quiz

Think back to the beginning of the course when we did a quiz on what operations are fast and what operations are not.

Takeaway: our intuition about what is fast and what is slow is often wrong.

Not just at a macro level, but at a micro level.

You may be able to narrow down that this computation of x is slow, but if you examine it carefully... what parts of it are slow?

Premature Optimization

Programmers waste enormous amounts of time thinking about, or worrying about, the speed of noncritical parts of their programs, and these attempts at efficiency actually have a strong negative impact when debugging and maintenance are considered. We should forget about small efficiencies, say about 97% of the time: premature optimization is the root of all evil. Yet we should not pass up our opportunities in that critical 3%.

– Donald Knuth

That Saying You Were Expecting

So going about this blindly is probably a waste of time.

You might be fortunate and optimize a slow part.

So, to make your programs or systems fast, you need to find out what is currently slow and improve it (duh!).

Up until now in the course it's mostly been about "let's speed this up", but we did not take much time to decide what we should speed up.

The general idea is, collect some data on what parts of the code are taking up the majority of the time.

This can be broken down into looking at what functions get called, or how long functions take, or what's using memory...

`printf`

There is always the “informal” way of doing this.

You probably know that when developing a program you can “debug” it without using any tools by inserting a lot of print statements to the console.

So when you enter function `foo` you print a nice little line on the console that say something like “entering function foo”, associated with a timestamp.

Then when you’re ready to return, a corresponding print function that says “exiting” appears, also with a timestamp.

Console Profiling

This approach kind of works, and I've used it myself to figure out what blocks of a single large function are taking a long time (updating exchange rates... yeah).

But this approach is not necessarily a good one.

It's an example of "invasive" profiling – we are going in and changing the source code of the program in question – to add instrumentation (log statements).

Plus we have to do a lot of manual accounting.

Assuming your program is fast and goes through functions quickly and often, trying to put the pieces together manually is hopeless.

Wizardry!

Also like debugging, if you get to be a wizard you can maybe do it by code inspection.

But that technique of speculative execution inside your head is a lot harder to apply to performance problems than it is to debugging.

So we should all agree, we want to use tools and do this in a methodical way.

So far we've been looking at small problems.

Must **profile** to see what takes time in a large program.

Two main outputs:

- flat;
- call-graph.

- Two main data gathering methods:
  - statistical;
  - instrumentation.

Profiler Outputs

Flat Profiler:

- Only computes the average time in a particular function.
- Does not include other (useful) information, like callees.

Call-graph Profiler:

- Computes call times.
- Reports frequency of function calls.
- Gives a call graph: who called what function?

Data Gathering Methods

Statistical:

Mostly, take samples of the system state, that is:

- every 100ms, check the system state.
- will cause some slowdown, but not much.

Instrumentation:
Add additional instructions at specified program points:

- can do this at compile time or run time (expensive);
- can instrument either manually or automatically;
- like conditional breakpoints.

Guide to Profiling

When writing large software projects:

- First, write clear and concise code.
  Don't do any premature optimizations—focus on correctness.
- Profile to get a baseline of your performance:
  - allows you to easily track any performance changes;
  - allows you to re-design your program before it's too late.

Focus your optimization efforts on the code that matters.

Things to Look For

Good signs:

- Time is spent in the right part of the system.
- Most time should not be spent handling errors; in non-critical code; or in exceptional cases.
- Time is not unnecessarily spent in the operating system.

`gprof` introduction

Statistical profiler, plus some instrumentation for calls.

Runs completely in user-space.

Only requires a compiler.

`gprof` usage

Use the `-pg` flag with `gcc` when compiling and linking.

Run your program as you normally would.

- Your program will now create a `gmon.out` file.

Use gprof to interpret the results: `gprof <executable>`.

gprof example

A program with 100 million calls to two math functions.

```
int main() {
    int i,x1=10,y1=3,r1=0;
    float x2=10,y2=3,r2=0;

    for(i=0;i<100000000;i++) {
        r1 += int_math(x1,y1);
        r2 += float_math(y2,y2);
    }
}
```

- Looking at the code, we have no idea what takes longer.
- Probably would guess floating point math taking longer.
- (Overall, silly example.)

Example (Integer Math)

```
int int_math(int x, int y){
    int r1;
    r1=int_power(x,y);
    r1=int_math_helper(x,y);
    return r1;
}

int int_math_helper(int x, int y){
    int r1;
    r1=x/y*int_power(y,x)/int_power(x,y);
    return r1;
}

int int_power(int x, int y){
    int i, r;
    r=x;
    for(i=1;i<y;i++){
        r=r*x;
    }
    return r;
}
```

Example (Float Math)

```
float float_math(float x, float y) {
    float r1;
    r1=float_power(x,y);
    r1=float_math_helper(x,y);
    return r1;
}

float float_math_helper(float x, float y) {
    float r1;
    r1=x/y*float_power(y,x)/float_power(x,y);
    return r1;
}

float float_power(float x, float y){
    float i, r;
    r=x;
    for(i=1;i<y;i++) {
        r=r*x;
    }
    return r;
}
```

When we run the program and look at the profile, we see:

```
Flat profile:

Each sample counts as 0.01 seconds.
  %   cumulative   self              self     total
 time   seconds   seconds    calls  ns/call  ns/call  name
 32.58      4.69     4.69 300000000    15.64    15.64  int_power
 30.55      9.09     4.40 300000000    14.66    14.66  float_power
 16.95     11.53     2.44 100000000    24.41    55.68  int_math_helper
 11.43     13.18     1.65 100000000    16.46    45.78  float_math_helper
  4.05     13.76     0.58 100000000     5.84    77.16  int_math
  3.01     14.19     0.43 100000000     4.33    64.78  float_math
  2.10     14.50     0.30                             main
```

- One function per line.
- **% time:** the percent of the total execution time in this function.
- **self:** seconds in this function.
- **cumulative:** sum of this function's time + any above it in table.

Flat Profile

```
Flat profile:

Each sample counts as 0.01 seconds.
  %   cumulative   self              self     total
 time   seconds   seconds    calls  ns/call  ns/call  name
 32.58      4.69     4.69 300000000    15.64    15.64  int_power
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 11.43     13.18     1.65 100000000    16.46    45.78  float_math_helper
  4.05     13.76     0.58 100000000     5.84    77.16  int_math
  3.01     14.19     0.43 100000000     4.33    64.78  float_math
  2.10     14.50     0.30                             main
```

- **calls:** number of times this function was called
- **self ns/call:** just self nanoseconds / calls
- **total ns/call:** average time for function execution, including any other calls the function makes

Call Graph Example (1)

After the flat profile gives you a feel for which functions are costly, you can get a better story from the call graph.

```
index % time    self  children    called     name
                                                 <spontaneous>
[1]     100.0    0.30   14.19                    main [1]
                 0.58    7.13 100000000/100000000     int_math [2]
                 0.43    6.04 100000000/100000000     float_math [3]
-----------------------------------------------
                 0.58    7.13 100000000/100000000     main [1]
[2]      53.2    0.58    7.13 100000000         int_math [2]
                 2.44    3.13 100000000/100000000     int_math_helper [4]
                 1.56    0.00 100000000/300000000     int_power [5]
-----------------------------------------------
                 0.43    6.04 100000000/100000000     main [1]
[3]      44.7    0.43    6.04 100000000         float_math [3]
                 1.65    2.93 100000000/100000000     float_math_helper [6]
                 1.47    0.00 100000000/300000000     float_power [7]
```

The line with the index is the current function being looked at **(primary line)**.

- Lines above are functions which called this function.
- Lines below are functions which were called by this function (children).

Primary Line

- **time:** total percentage of time spent in this function and its children
- **self:** same as in flat profile
- **children:** time spent in all calls made by the function
  - should be equal to self + children of all functions below

Reading Callers from Call Graph

Callers (functions above the primary line)

- **self:** time spent in primary function, when called from current function.
- **children:** time spent in primary function's children, when called from current function.
- **called:** number of times primary function was called from current function / number of nonrecursive calls to primary function.

Reading Callees from Call Graph

Callees (functions below the primary line)

- **self:** time spent in current function when called from primary.
- **children:** time spent in current function's children calls when called from primary.
  - self + children is an estimate of time spent in current function when called from primary function.
- **called:** number of times current function was called from primary function / number of nonrecursive calls to current function.

Call Graph Example (2)

```
index % time    self  children    called     name

                2.44    3.13 100000000/100000000      int_math [2]
[4]     38.4    2.44    3.13 100000000          int_math_helper [4]
                3.13    0.00 200000000/300000000      int_power [5]
-----------------------------------------------
                1.56    0.00 100000000/300000000      int_math [2]
                3.13    0.00 200000000/300000000      int_math_helper [4]
[5]     32.4    4.69    0.00 300000000          int_power [5]
-----------------------------------------------
                1.65    2.93 100000000/100000000      float_math [3]
[6]     31.6    1.65    2.93 100000000          float_math_helper [6]
                2.93    0.00 200000000/300000000      float_power [7]
-----------------------------------------------
                1.47    0.00 100000000/300000000      float_math [3]
                2.93    0.00 200000000/300000000      float_math_helper [6]
[7]     30.3    4.40    0.00 300000000          float_power [7]
```

We can now see where most of the time comes from, and pinpoint any locations that make unexpected calls, etc.

This example isn't too exciting; we could simplify the math.

Summary (Profiling)

- Saw how to use `gprof`
- Profile early and often.
- Make sure your profiling shows what you expect.