15-213

Performance Evaluation

May 2, 2000

Topics

- Getting accurate measurements
- Amdahl's Law

"Time" on a Computer System

= user time *(time executing instructing instructions in the user process)*

= system time *(time executing instructing instructions in kernel on behalf of user process)*

= some other user's time *(time executing instructing instructions in different user's process)*

+ + = real (wall clock) time

We will use the word "time" to refer to user time.

Time of Day Clock

- return elapsed time since some reference time (e.g., Jan 1, 1970)
- example: Unix `gettimeofday()` command
- coarse grained (e.g., ~3msec resolution on Linux, 10 msec resolution on Windows NT)
  - Lots of overhead making call to OS
  - Different underlying implementations give different resolutions

```
#include <sys/time.h>
#include <unistd.h>

  struct timeval tstart, tfinish;
  double tsecs;
  gettimeofday(&tstart, NULL);
  P();
  gettimeofday(&tfinish, NULL);
  tsecs = (tfinish.tv_sec - tstart.tv_sec) +
      1e6 * (tfinish.tv_usec - tstart.tv_usec);
```


Interval (Count-Down) Timers

- set timer to some initial value
- timer counts down toward zero
- coarse grained (e.g., 10 msec resolution on Linux)

```
void init_etime() {
  first.it_value.tv_sec
     = 86400;
  setitimer(ITIMER_VIRTUAL,
           &first, NULL);
}
```

```
double get_etime() {
  struct itimerval curr;
  getitimer(ITIMER_VIRTUAL,&curr);
  return(double)(
      (first.it_value.tv_sec -
        curr.it_value.tv_sec) +
      (first.it_value.tv_usec -
        curr.it_value.tv_usec)*1e-6);
```

Using the interval timer

```
init_etime();
secs = get_etime();
P();
secs = get_etime() - secs;
printf("%lf secs\n", secs);
```

Cycle Counters

- **Most modern systems have built in registers that are incremented every clock cycle**
  - Very fine grained
  - Maintained as part of process state
    - » Save & restore with context switches
    - » Counter will reflect time spent by user process
- **Special assembly code instruction to access**
- **On (recent model) Intel machines:**
  - 64 bit counter.
  - RDTSC instruction sets `%edx` to high order 32-bits, `%eax` to low order 32-bits

Wrap Around Times for 550 MHz machine

- **Low order 32-bits wrap around every 2^{32} / (550 * 10^6) = 7.8 seconds**
- **High order 64-bits wrap around every 2^{64} / (550 * 10^6) = 33539534679 seconds**
  - 1065.3 years

Using the Cycle Counter

- **Example**
  - Function that returns number of cycles elapsed since previous call to function
  - Express as `double` to avoid overflow problems

```
/* Keep track of most recent reading of cycle counter */
static unsigned cyc_hi = 0;
static unsigned cyc_lo = 0;

static double delta_cycles()
{
  unsigned ncyc_hi, ncyc_lo;
  double result;
  /* Get cycle counter as ncyc_hi and ncyc_lo */
  . . .
  /* Do double precision subtraction */
  . . .
  cyc_hi = ncyc_hi; cyc_lo = ncyc_lo;
  return result;
}
```


Accessing the Cycle Counter (cont.)

- **GCC allows inline assembly code with mechanism for matching registers with program variables**
- **Code only works on x86 machine compiling with GCC**

```
unsigned ncyc_hi, ncyc_lo;
/* Get cycle counter */
asm("rdtsc\nmovl %%edx,%0\nmovl %%eax,%1"
    : "=r" (ncyc_hi), "=r" (ncyc_lo)
    : /* No input */
    : "%edx", "%eax");
```

- **Emit assembly with `rdtsc` and two `movl` instructions**
- **Code generates two outputs:**
  - **Symbolic register `%0`** should be used for `ncyc_hi`
  - **Symbolic register `%1`** should be used for `ncyc_lo`
- **Code has no inputs**
- **Registers `%eax` and `%edx` will be overwritten**

Accessing the Cycle Counter (cont.)

Emitted Assembly Code

```
 delta_cycles:
  pushl %ebp          # Stack stuff
  movl %esp,%ebp
  pushl %esi
  pushl %ebx
#APP
  rdtsc               # Result of ASM Statement
movl %edx,%esi        # Uses %esi for ncyc_hi
movl %eax,%ecx        # Uses %ecx for ncyc_lo
#NO_APP
  movl %ecx,%ebx      # ncyc_lo
  subl cyc_lo,%ebx
  cmpl %ecx,%ebx
  seta %al
  xorl %edx,%edx
  movb %al,%dl
  movl %esi,%eax      # ncyc_hi
```

Using the Cycle Counter (cont.)

```
/* Keep track of most recent reading of cycle
counter */
static unsigned cyc_hi = 0;
static unsigned cyc_lo = 0;

static double delta_cycles()
{
  unsigned ncyc_hi, ncyc_lo;
  unsigned hi, lo, borrow;
  double result;
  . . .
  /* Do double precision subtraction */
  lo = ncyc_lo - cyc_lo;
  borrow = lo > ncyc_lo;
  hi = ncyc_hi - cyc_hi - borrow;
  result = (double) hi * (1 << 30) * 4 + lo;
  . . .
}
```


Timing with Cycle Counter

```
double tsecs;
delta_cycles();
P();
tsecs = delta_cycles() / (MHZ * 1e6);
```


Measurement Pitfalls

Overhead

- **Calling `delta_cycles()` incurs small amount of overhead**
- **Want to measure long enough code sequence to compensate**

Unexpected Cache Effects

- **artificial hits or misses**
- **e.g., these measurements were taken with the Alpha cycle counter:**

```
foo1(array1, array2, array3);       /* 68,829 cycles */
foo2(array1, array2, array3);       /* 23,337 cycles */
   vs.
foo2(array1, array2, array3);       /* 70,513 cycles */
foo1(array1, array2, array3);       /* 23,203 cycles */
```


Dealing with Overhead & Cache Effects

- **Keep doubling number of times execute P() until reach some threshold**
  - Used CMIN = 50000

```
int cnt = 1;
double cmeas = 0;
double cycles;
do  {
  int c = cnt;
  P();                 /* Warm up cache */
  (void) delta_cycles();
  while (c-- > 0)
    P();
  cmeas = delta_cycles();
  cycles = cmeas / cnt;
  cnt += cnt;
} while (cmeas < CMIN);  /* Make sure have enough */
return cycles / (1e6 * MHZ);
```

Context Switching

Context switches can also affect cache performance

- **e.g., (`foo1`, `foo2`) cycles on an unloaded timing server:**
  - » 71,002, 23,617
  - » 67,968, 23,384
  - » 68,840, 23,365
  - » 68,571, 23,492
  - » 69,911, 23,692

Why Do Context Switches Matter?

- **Cycle counter only accumulates when running user process**
- **Some amount of overhead**
- **Caches polluted by OS and other user's code & data**
  - – Cold misses as restart process

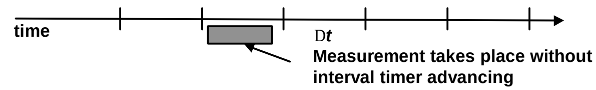
Measurement Strategy

- **Try to measure uninterrupted code execution**

Detecting Context Switches

Clock Interrupts

- **Processor clock causes interrupt every Δt seconds**
  - – Typically D*t* = 10 ms
  - – Same as interval timer resolution



- **Can detect by seeing if interval timer has advanced during measurement**

```
start = get_etime();

/* Perform Measurement */
  . . .
if (get_etime() - start > 0)
   /* Discard measurement */
```


Detecting Context Switches (Cont.)

External Interrupts

- **E.g., due to completion of disk operation**
- **Occur at unpredictable times but generally take a long time to service**

Detecting

- **See if real time clock has advanced**
  - – Using coarse-grained interval timer

```
start = get_rtime();

/* Perform Measurement */
  . . .
if (get_rtime() - start > 0)
   /* Discard measurement */
```

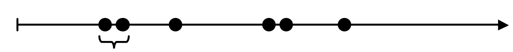
Reliability

- **Good, but not 100%**
- **Can't get clean measurements on heavily loaded system**

Improving Accuracy

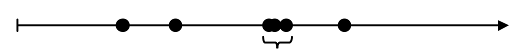
Current Timer Code

- **Assume that bad measurements always overestimate time**
  - – True if main problem is due to context switches
- **Take multiple samples (2–10) until lowest two are within some small tolerance of each other**



Better Timing Code

- **Erroneous measurements both under- and over-estimate time, but are not correlated to each other**
- **Look for clustering of times among samples**



Measurement Summary

It's difficult to get accurate times

- **compensating for overhead**
- **but can't always measure short procedures in loops**
  - global state
  - mallocs
  - changes cache behavior

It's difficult to get repeatable times

- **cache effects due to ordering and context switches**

Moral of the story:

- **Adopt a healthy skepticism about measurements!**
- **Always subject measurements to sanity checks.**

Amdahl's Law

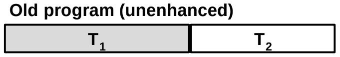
You plan to visit a friend in Normandy France and must decide whether it is worth it to take the Concorde SST ($3,100) or a 747 ($1,021) from NY to Paris, assuming it will take 4 hours Pgh to NY and 4 hours Paris to Normandy.

	time NY → Paris	total trip time	speedup over 747
747	8.5 hours	16.5 hours	1
SST	3.75 hours	11.75 hours	1.4

Taking the SST (which is 2.2 times faster) speeds up the overall trip by only a factor of 1.4!

Speedup

Old program (unenhanced)

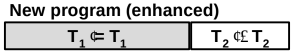


Old time: $T = T_1 + T_2$

T_1 = time that can NOT be enhanced.

T_2 = time that can be enhanced.

New program (enhanced)



New time: $T' = T_1' + T_2'$

T_2' = time after the enhancement.

Speedup: $S_{overall} = T / T'$

Computing Speedup

Two key parameters:

$F_{enhanced} = T_2 / T$ (fraction of original time that can be improved)
$S_{enhanced} = T_2 / T_2'$ (speedup of enhanced part)

$T' = T_1' + T_2' = T_1 + T_2' = T(1-F_{enhanced}) + T_2'$
$= T(1 - F_{enhanced}) + (T_2/S_{enhanced})$ [by def of $S_{enhanced}$]
$= T(1 - F_{enhanced}) + T(F_{enhanced} / S_{enhanced})$ [by def of $F_{enhanced}$]
$= T((1 - F_{enhanced}) + F_{enhanced}/S_{enhanced})$

Amdahl's Law:

$$S_{overall} = T / T' = 1/((1 - F_{enhanced}) + F_{enhanced}/S_{enhanced})$$

Key idea:

- Amdahl's Law quantifies the general notion of diminishing returns.
- It applies to any activity, not just computer programs.

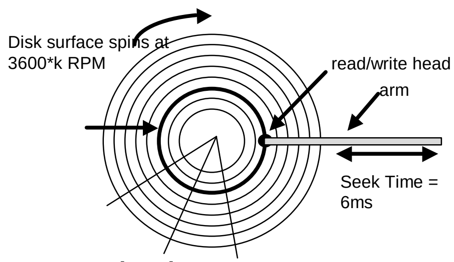
Amdahl's Law Example

Trip example:

- **Suppose that for the New York to Paris leg, we now consider the possibility of taking a rocket ship (15 minutes) or a handy rip in the fabric of space-time (0 minutes):**

	time NY->Paris	total trip time	speedup over 747
747	8.5 hours	16.5 hours	1
SST	3.75 hours	11.75 hours	1.4
rocket	0.25 hours	8.25 hours	2.0
rip	0.0 hours	8 hours	2.1

Magnetic Disk Example



Average Rotational Latency

- **1/2 revolution takes 1 / (120 * k) seconds = 8.5/k milliseconds**

Total Latency:

- **k = 1: 14.5 ms 1.0X**
- **k = 4: 8.1 ms 1.8X**

Lesson from Amdahl's Law

Useful Corollary of Amdahl's law:

- $1 \le S_{overall} \le 1 / (1 - F_{enhanced})$

$F_{enhanced}$	Max $S_{overall}$	$F_{enhanced}$	Max $S_{overall}$
0.0	1	0.9375	16
0.5	2	0.96875	32
0.75	4	0.984375	64
0.875	8	0.9921875	128

Moral: It is hard to speed up a program.

Moral++ : It is easy to make premature optimizations.

Other Maxims

Second Corollary of Amdahl's law:

- **When you identify and eliminate one bottleneck in a system, something else will become the bottleneck**

Beware of Optimizing on Small Benchmarks

- **Easy to cut corners that lead to asymptotic inefficiencies**
  - E.g., Intel's string hash function