CMSC 313
Introduction to Computer Systems
Lecture 24
Optimization

Alan Sussman
als@cs.umd.edu

Administrivia

- Project 6 due next Thursday, 12/10
  - public tests posted
- Project 4 grades and results made visible tomorrow
  - and email with style grades
- Read Chapter 5 of Bryant and O'Hallaron

Chapter 5, Bryant & O'Hallaron

Optimizing Program Performance

How processors spend their time

- Not all instructions take the same amount of time; some are more expensive
- Processors have caches to keep copies of recently accessed memory locations in fast storage
  - a recently accessed memory location is more likely to be accessed again soon
  - each cache item stores multiple data items (called the *line size*)
  - the same instruction may take different amounts of time different times it's executed - misses from the cache can be ten to a hundred times slower
  - efficiency will be maximized if the same cache items are used multiple times

Understanding modern processors

- It's helpful to know a bit about what a compiler can and can't do, as well as what takes time on the hardware
- Pipelining
  - parts of multiple instructions can execute simultaneously, such as decoding one instruction while loading the next one from memory
- Branch prediction
  - the processor guesses which way a branch will go, which allows the pipeline to stay full
- Superscalar processors can execute two or more instructions at once
- Some floating point operations (e.g., division) can take longer than integer (or other f.p.) operations
  - perhaps 5 to 10 times longer for the same operation

Issues in conducting measurements

- Number of runs:
  - a single run of a program to time its performance is not sufficient - many things go on in a computer, such as operating system functions and other programs running
  - multiple runs provide increased accuracy
  - take the mean of the K fastest runs
- Workload:
  - what data is the program given for measurement runs- does it look like a "typical" use of the program?
  - many algorithms might look good if the measured workload is too small – for small n, $O(n^2)$ algorithms are similar to O(n)
  - many algorithms might also look good if the measured workload is too large (not representative of the typical usage pattern)

Sources of performance problems

- I/O operations that are too small
  - reading one or a few characters at a time
- Debugging **`printf`**'s were left in the program
- Poor basic algorithms
  - $O(n^2)$ algorithms were used in cases where n was large, or for frequently performed operations
- Algorithms were used that compose poorly
- Cache memory performance
  - Reuse each cached item at least once if possible

Improving code performance

- This is **not** about algorithms, but rather:
  - how to convert algorithms into efficient code
  - how to refine code to make it run faster
- The key ideas are:
  - be systematic and data-driven in what you do (it's easy to just make random code changes without improving things)
  - programs spend their time in loops or recursion (a sequence of code executed once is fast), and in doing I/O

Know your compiler

- Compilers can be asked to "optimize" your code
  - the **gcc –O** flag (and **–O***N*) enables the optimizer, which makes modifications to the compiled program if possible
  - optimization is supposed to never break your code- only safe changes to the program are permitted
  - optimization should never alter correct programs
    - but it may discover **latent** bugs
- Limits on compiler optimizations:
  - the compiler has a limited understanding of the program
  - there's a need to compile programs quickly

Sample compiler optimization

- Original code:

```
int i, j, k;
...
for (i = 0; i < 200; i++)
  a[2 * j + i] = j * k + i;
```

- Optimized code:

```
int i, j, k;
...
int prod_2j, prod_jk;
prod_2j = 2 * j;
prod_jk = j * k;
for (i = 0; i < 200; i++)
  a[prod_2j + i] = prod_jk + i;
```


Typical compiler optimizations

- Code motion
  - previous example
- Loop unrolling
  - things can often be faster if a loop body is a bit bigger, because modern processors can perform several instructions (or at least parts of them) simultaneously
  - convert:

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

  - to:

```
for (i = 0; i < n; i += 2) {
  c[i] = a[i] + b[i];
  c[i + 1] = a[i + 1] + b[i + 1];
}
```

- Dead code elimination
  - if the compiler can infer that some code can never be executed, the code can be removed

Limits to compiler optimization

- Consider:

```
void func1(int *xp, int *yp) {
  *xp += *yp;
  *xp += *yp;
}
```

  Could this be replaced by the following version?

```
void func1(int *xp, int *yp) {
  *xp += 2 * *yp;
}
```

- If a function ends with
  `return f(x) + f(x) + f(x) + f(x);`
  can it be simplified to the following?
  `return 4 * f(x);`

Common code changes- loop bound checks

- Consider:

```
for (i = 0; i < strlen(data); i++)
  if (data[i] >= 'a' && data[i] <= 'z')
    data[i] -= ('a' - 'A');
```

- **`strlen()`** is called each time, but its result doesn't change inside the loop
  - this results in $O(n^2)$ performance
- Change to:

```
int difference = 'a' – 'A';
int limit = strlen(data);
for (i = 0; i < limit; i++)
  if (data[i] >= 'a' && data[i] <= 'z')
    data[i] -= difference;
```

- A compiler may not be able to figure the **`strlen()`** optimization out

Common code changes, con't.

- Recall:

```
int difference = 'a' – 'A';
int limit = strlen(data);
for (i = 0; i < limit; i++)
  if (data[i] >= 'a' && data[i] =< 'z')
    data[i] -= difference;
```

- The **`strlen()`** call can be eliminated entirely:

```
int difference = 'a' – 'A';
ptr = data;
while (*ptr != '\0') {
  if (*ptr >= 'a' && *ptr =< 'z')
    *ptr -= difference;
  ptr++;
}
```


Common code transformation- don't write small functions

- Functions calls take time
  - to set up the runtime stack when calling a function, and to return when done
- Small functions of one or two lines are not that useful:
  - they take more time to set up things for the call and to return afterward, than the time it takes to perform the function's instructions
  - they also provide relatively little isolation of ideas
- Try to define abstractions so the work to be done is larger than a few lines
- Sometimes you can use macros in place of small functions

Approach to applying these techniques

- For a large program it's hard to know where to start to optimize
- Start with **`gprof`** data and concentrate on the parts of the program that take the most time
- Amdahl's Law:
  - if you're tuning a function that takes α fraction (%) of the program execution time T
  - and you can make it k times faster
  - $T_{new} = (1 - \alpha)\, T_{old} + (\alpha T_{old})/k$
  - you're basically limited by how big α is

Types of optimizations

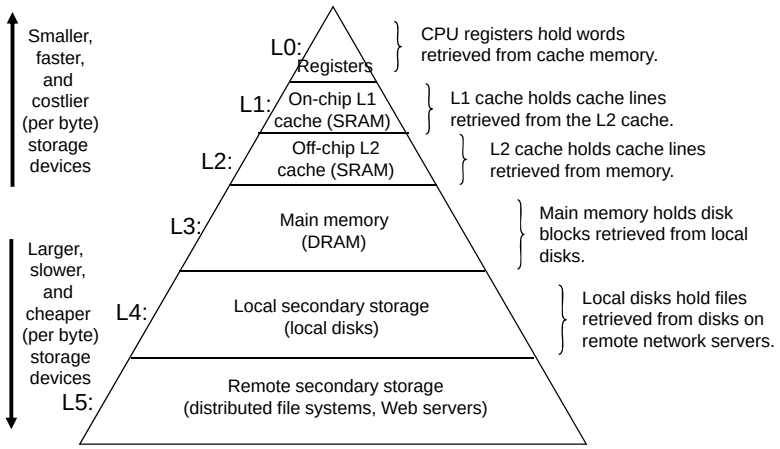
- Optimizations you should do regardless of the processor/compiler:
  - code motion (moving code out of a loop)
  - reducing function calls (e.g., inlining)
  - reduce/remove unneeded memory usage
  - share common subexpressions
- Machine-dependent optimization
  - pointer code
  - loop unrolling
  - enabling instruction-level parallelism

Storage and access order matters

- The layout of data items in memory means that if we access things in a different order, we can get wildly different execution times
- Memory hierarchy:

Type of storage	Access time (CPU cycles)
registers	1
cache (1st level)	~2-3
memory	~10-100

More detailed memory hierarchy



Two kinds of locality

- Principle of locality:
  - programs tend to reuse data and instructions near those they have used recently, or that were recently referenced themselves
  - temporal locality: recently referenced items are likely to be referenced again in the near future
  - spatial locality: items with nearby addresses tend to be referenced close together in time

Locality example

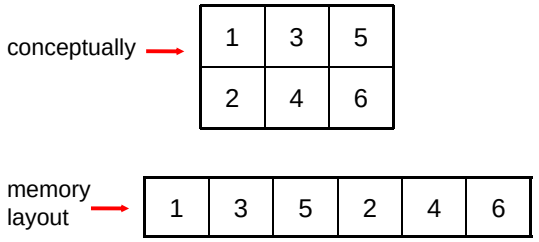
```
sum = 0;
for (i = 0; i < n; i++)
  sum += a[i];
return sum;
```

- Data
  - reference array elements in succession (in the same order they're stored in memory)
  - reference **sum** each iteration
- Instructions
  - reference instructions in sequence
  - cycle through loop repeatedly

Aside: Multidimensional array storage

- In C, array elements are stored in row major order in memory, meaning each row's elements are stored in adjacent locations in order by column subscript, and all of the rows are adjacent in memory, stored in order by row subscript.

```
int a[2][3] =  {{1, 3, 5}, {2, 4, 6}};
```



A dramatic locality example

```
#define ROWS 20000
#define COLS 20000

int main() {
  int arr[ROWS][COLS];
  int i, j, sum = 0;
  struct rusage usage1, usage2;

  for (i = 0; i < ROWS; i++)
    for (j = 0; j < COLS; j++)
      arr[i][j] = rand();
  getrusage(RUSAGE_SELF, &usage1);
  for (i = 0; i < ROWS; i++)
    for (j = 0; j < COLS; j++)
      sum += arr[i][j];
  getrusage(RUSAGE_SELF, &usage2);
  printf("sum = %d\n", sum);
  /* calculate user time, store in usage2 */
  printf("User time %d.%06ds\n", (int) usage2.ru_utime.tv_sec,
         (int) usage2.ru_utime.tv_usec);
  return 0;
}
```


A dramatic locality example

```
#define ROWS 20000
#define COLS 20000

int main() {
  int arr[ROWS][COLS];
  int i, j, sum = 0;
  struct rusage usage1, usage2;

  for (i = 0; i < ROWS; i++)
    for (j = 0; j < COLS; j++)
      arr[i][j] = rand();
  getrusage(RUSAGE_SELF, &usage1);
  for (j = 0; j < COLS; j++)
    for (i = 0; i < ROWS; i++)
      sum += arr[i][j];
  getrusage(RUSAGE_SELF, &usage2);
  printf("sum = %d\n", sum);
  /* calculate user time, store in usage2 */
  printf("User time %d.%06ds\n", (int) usage2.ru_utime.tv_sec,
         (int) usage2.ru_utime.tv_usec);
  return 0;
}
```

Other caching optimizations

- Memoization
  - we can store intermediate results to speed up our calculations
  - C requires us to do this explicitly (some languages have support for doing this automatically)

Standard Fibonacci code

```
#include <stdio.h>
#include <stdlib.h>

/* Return the nth Fibonacci number
 * (fib(0) = fib(1) = 1)
 */
unsigned long fib(unsigned int n) {
  if (n == 0 || n == 1)
    return 1;
  return fib(n-1) + fib(n-2);
}

int main(int argc, char *argv[]) {
  int num = atoi(argv[1]);
  printf("%lu\n", fib(num));
  return 0;
}
```


Pruning the recursion tree

- This version of the Fibonacci function is quite slow
- We recompute values we've already computed!
- If we cache these computed values explicitly, we can speed things up dramatically

Memoized Fibonacci code

```
#include <stdio.h>
#include <stdlib.h>

/* Return the nth Fibonacci number
 * (fib(0) = fib(1) = 1)
 */
unsigned long fib(unsigned int n) {
  static unsigned int table[100] = {0};
  if (n == 0 || n == 1)
    return 1;
  if (table[n])
    return table[n];
  return table[n] = fib(n-1) + fib(n-2);
}

int main(int argc, char *argv[]) {
  int num = atoi(argv[1]);
  printf("%lu\n", fib(num));
  return 0;
}
```