CS61 Section 7 Notes

Week 11/5-11/9

0. I/O and File Descriptors

I/O System Calls, File Descriptors

For more information: `man 2 <system-call>`

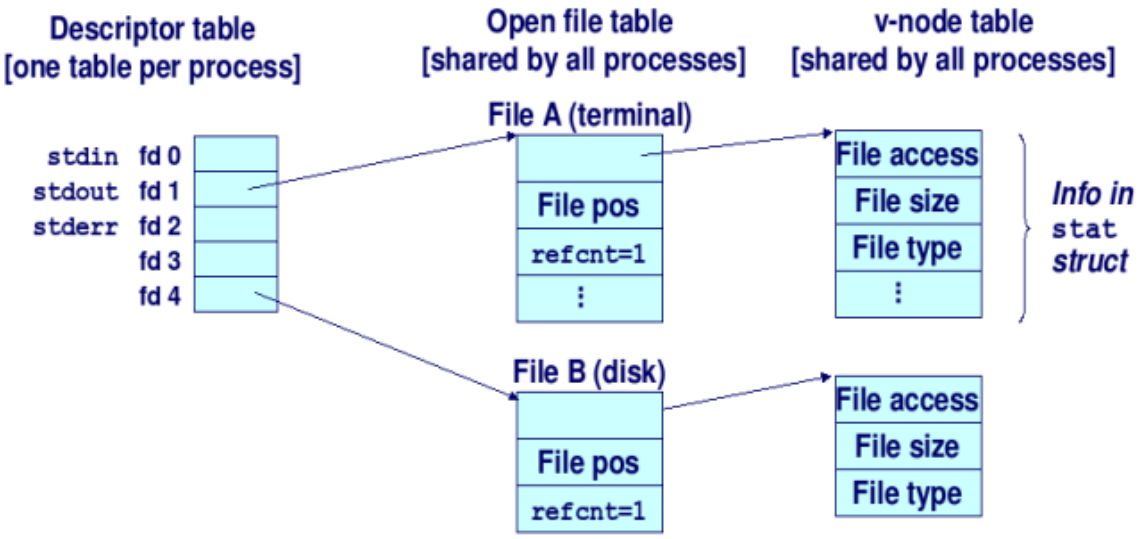
```
int open(const char *path, int oflag, ...)
```

- system call; open a file with the given path and flags
- returns a ***file descriptor*** for the file (non-negative), or -1 on failure

oflag is obtained by or-ing these values together (see more flags in the man page)

O_RDONLY	open for reading only
O_WRONLY	open for writing only
O_RDWR	open for reading and writing
O_CREAT	create file if it does not exist
O_TRUNC	truncate size to 0
O_SYNC	synchronous call--write directly to disk

The kernel maintains a ***descriptor table*** for each process to maintain a list of all opened resources for I/O, such as files. A ***file descriptor*** is an index into this table.



When the process starts, file descriptor 0 refers to ***stdin*** (the input stream, i.e. when the console prompts the user for input), file descriptor 1 refers to ***stdout*** (the output stream, i.e. where your printf statements print to), and file descriptor 2 refers to ***stderr*** (the error stream, used to report errors in code, and is usually printed out to console).

Whenever we call open, the kernel assigns a new file descriptor for the opened file. ***It is important to note that a file descriptor is NOT the file itself--it is an index into the kernel's descriptor table for the process***. Using file descriptors, the kernel keeps track of data associated with the file, such as the size of the file, permissions of the file, where the current cursor is in the file, and so forth.

`ssize_t read(int fildes, void *buf, size_t nbyte)`

- system call
- attempts to read nbyte worth of bytes into buf from the given file descriptor fildes
- may actually return a value less than nbyte (if the call read fewer than nbytes), or return -1 on error

`ssize_t write(int fildes, const void *buf, size_t nbyte)`

- system call
- attempts to write nbyte worth of bytes from buf to the given file descriptor fildes
- may actually return a value less than nbyte (if the write command wrote fewer than nbytes), or return -1 on error

`int close(int fildes)`

- system call
- closes the file descriptor and returns 0 on success, -1 on error
- it is important that we close all files that we do not need to allow the OS to reclaim resources

Standard I/O (stdio)

The stdio library is a wrapper for I/O system calls that performs buffering. The purpose of the stdio library is to speed up I/O calls by (1) reducing the amount of system calls, and (2) caching data being read/written. See the man page for more information: `man 3 <library-call>`

```
FILE *fopen(const char *restrict filename, const char *restrict mode);
```

- Instead of returning a file descriptor, this returns a pointer to a FILE struct

```
size_t fread(void *restrict ptr, size_t size, size_t nitems, FILE *restrict
stream);
```

- reads size * nitems bytes into buffer ptr from the FILE pointer stream
- performs buffered I/O--the stdin library maintains a cache of data so that subsequent reads are faster
- returns the actual number of ***items*** read

```
size_t fwrite(const void *restrict ptr, size_t size, size_t nitems, FILE
*restrict stream);
```

- writes nitems * size bytes from ptr into the FILE pointer stream
- performs buffered I/O--the stdin library batches write requests to minimize the number of system calls

```
int fclose(FILE *stream);
```

- stdin library version of close

1. Locality

Locality of Reference - property of code such that data access at time t is close to data accessed at t + 1

QUESTION. Does sequential access have good locality or bad locality?
Good--accessing A[i] gives a good prediction of where the next memory access will be

QUESTION. Does random accessing an array have good locality or bad locality?
Bad--accessing A[i] does not tell us where the next memory access will be

QUESTION. Throwback to the first lecture. Consider a list implemented as a resizable array (using the vector pattern), and a list implemented as a linked list. For iterating over the collection, which implementation provides better locality?

- vector because items are in adjacent addresses in memory
- linked list nodes are scattered randomly in memory, bad locality
    - lead to cache misses, and therefore slower to iterate

2. Caches

Cache - Fast storage that stores temporary copies of data from slower storage

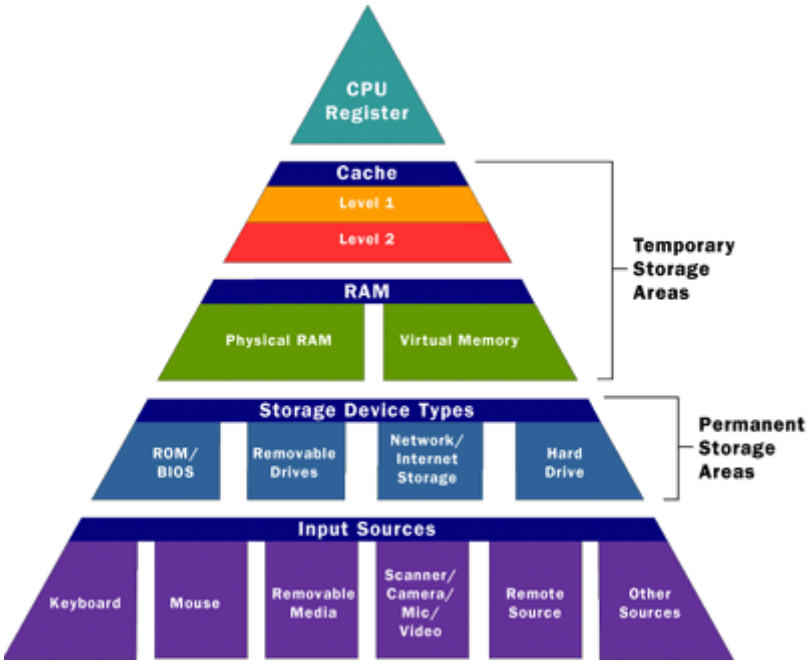
If we are looking for an item and it is in our cache, we say that we have a ***cache hit***. If the item we are looking for is not in our cache, we say that we have a ***cache miss***.

Caches allow us to store data closer to where it is actively being used, and therefore allow retrieval of the data to be faster. An analogy of a cache would be your backpack. You keep some books and other items in your bag so that you can quickly retrieve the items when you are at classes. It would be extremely inconvenient and slow to go back to your room every time just to pick up an item. **Thus, your backpack is a cache for your room.**

Taking this to another level, you can think of **your school dorm room as a cache for your room back in your hometown**. If you didn't live in Boston, it would be even more slow and inconvenient to have to go back to your hometown every time you needed an item--instead, you ***speculate*** about what you would need for the semester and take what you need with you when you move into your dorm room. Note that for each level of our "cache"--your backpack for your dorm room, and your dorm room for your hometown--the cache is smaller, but a lot faster to access.

The computer memory hierarchy acts in a very similar way. Below is a diagram of the ***memory hierarchy*** of a computer. The higher you go up, the faster it is to access items. The lower you go up, the cheaper it is to add more storage in that layer.

KEY INSIGHT: Each level is a cache for the levels below! Thus, registers can be thought of as a cache for primary storage (RAM). Primary storage can be thought of as a cache for disk.



3. Request Costs

Define:

R = **per request overhead [seconds / requests]**
U = **per unit overhead,** for some definition of "unit" **[seconds / byte]**
C = total cost **[seconds]**

Then: C = # requests * R + # bytes * U

Suppose we are writing a file of size **N = 10^6** bytes to disk. Similar to `w01-syncbyte.c`, we write each byte individually and synchronously to disk, and we observed the total time to write all N bytes to be **1.01s**. Similar to `w02-syncblock.c`, we write blocks of size 1000 to disk. We observed that the total time to write all N/1000 blocks to disk takes **0.011s**.

QUESTION: Write down an equation in terms of N, R, and U that describes how long it took to write each byte individually to disk.

N * R + N * U = 1.01s

QUESTION: Write down an equation in terms of N, R, and U that describes how long it took to write blocks of bytes of size 1000 to disk.

(N / 1000) * R + N * U = 0.011s

QUESTION: What are the per request overhead (R) and per unit overhead (U)?

Subtract the two equations:

(999N / 1000) * R = 0.999s
R = 10^(-6) s = 1 microsecond
U = 10^(-8) s

QUESTION: How long would it take if we instead wrote blocks of bytes of size 4000 to disk?

(N / 4000) * R + N * U = (10^6 / 4000) * 10^(-6) + 10^6 * 10^(-8) = 0.01025 sec

4. Caching Strategies

Increasing Block Size When Writing

In `w01-syncbyte.c -> w02-syncblock.c`

We go from: `write(fd, buf, 1)`
to: `write(fd, buf, block_size)`

where we changed `block_size`, varying from 512 to 2^16 and 10 * 2^20 (10 megabytes). Also, note that both of these calls were ***synchronous*** (synchronous here means that each write call causes the operating system to write directly to disk for each write call). We noticed in lecture that `w01-syncbyte` was EXTREMELY slow in comparison to `w02-syncblock`.

QUESTION. Why did changing the write call from 1 byte to a larger block size improve the rate at which we wrote to disk?
Writing to disk has an extremely high per request cost R (system call overhead + disk seek + rotational latency). Thus, by doing more units of work for each request, we decrease the total cost of writing our entire file to disk.

QUESTION. What are the disadvantages still about w02-syncblock.c?

- System call overhead for every write
- Synchronous write for every write

Batching Requests

Batching - group requests to reduce per request overhead

In our backpack cache example, batching would be like waiting until you go back to your room to get all the things that you need at once, rather than going back to your room every time you needed something back in your room.

QUESTION: In terms of per unit overhead and per request overhead, when would batching be useful?
Batching is useful when per request overhead R is high--by batching requests together, we can use only one request to allow more units of work to be done.

Consider the changes in these file pairs:

```
w01-syncbyte.c -> w03-byte.c
w02-syncblock.c -> w04-block.c
```

In both of these file pairs, our only changes were removing the `O_SYNC` flag in our call to open, thus making our system calls for write no longer synchronous.

We noticed that in each pair, removing the `O_SYNC` flag dramatically increased the rate at which we wrote to disk.

QUESTION: What is causing this speedup? Are we using a cache? If so, where is the cache located in the memory hierarchy, and who controls access to the cache?

- Speedup is caused by batching requests together
  - **reduce the number of disk seeks**
  - User process executes write system call
  - Kernel writes to buffer cache, returns quickly back to the user process
- For each file being written to, the kernel maintains a buffer cache in DRAM of things to be written to disk
  - The kernel writes each write request by a user process to the cache instead of directly to disk
- When the cache fills up (or every so often, ~30 seconds), the kernel writes the requests in the cache to disk.
  - Viewed from the user process, these requests are written ***asynchronously*** to disk (the first request may actually be executed long after the user process originally issued the request).

QUESTION: Why is `w04-block.c` still faster than `w03-byte.c`?

- w04-block has fewer system calls, therefore reducing the per request cost R

QUESTION: What are still some disadvantages with `w03-byte.c` and `w04-block.c`?

- Batching requests leaves open the possibility of inconsistent data
  - If your machine fails when requests are still buffered and not yet written to disk, those requests will never reach the disk.
- Each write call is making a system call, which is very expensive (exceptional control flow)

Using stdio

Consider the changes in these file pairs:

```
w03-byte.c -> w05-stdiobyte.c
w04-block.c -> w06-stdioblock.c
```

In these file pairs, we replaced the system calls `open` and `write` with library calls to the stdio (Standard I/O) library functions `fopen` and `fwrite`. We noticed in lecture that there was an even greater rate at which we wrote to disk.

QUESTION: What is causing this speedup? Are we using a cache? If so, where is the cache located in the memory hierarchy, and who controls access to the cache?

- stdio library maintains a cache in DRAM
- every time the user calls fwrite, the stdio library writes request to cache
    - when cache fills up (1 page size), the stdio library executes the write system call with the entire page
    - kernel writes this page to its own buffer cache (see above)
- we have a speedup because **we reduce the number of system calls** and therefore reduce the per request cost R

QUESTION: Why is `w06-stdioblock.c` still faster than `w05-stdiobyte.c`?

- w06-stdioblock.c has fewer invocations to fwrite, reducing overhead of the fwrite function call (e.g. stack frame allocation)

QUESTION: What are still some disadvantages with `w05-stdiobyte.c` and `w06-stdioblock.c`?

- How do you handle writes that are not occurring sequentially? (not sure about this)

Speculation and Read-Ahead (Prefetching)

Speculation - performing work BEFORE an explicit request for the work; purpose is to speed up future requests

Read-Ahead (Prefetching) - read data in advance of explicit read requests for the data. Read-Ahead is an example of speculation.

Back in our backpack example--every day, you leave your room with a few select items in your bag. You ***speculated*** that you would need item X and item Y during your day BEFORE you made an explicit request for item X and item Y, hence you placed X and Y into your bag.

In r01-byte.c and r02-block.c, we make direct read system calls.

QUESTION: What is the kernel doing to speed up read requests?

- Kernel maintains a buffer cache in DRAM
    - on first read, prefetch more data than the actual requests
    - whenever the user wants to read more data, the data is already in the cache

QUESTION: What are disadvantages with r01-byte.c and r02-block.c?

- system calls for every read

In `r04-stdiobyte.c` and `r05-stdioblock.c`, we replaced the read system calls with stdio library calls to fread, and we noticed a higher rate of reading from disk.

QUESTION: What is causing this speedup? Are we using a cache? If so, where is the cache located in the memory hierarchy, and who controls access to the cache?

- stdio maintains a 1 page sized cache
    - on first read, stdio prefetches more data than the actual request
    - when user reads more data, data is already in cache
    - combine this with kernel's buffer cache
- fewer system calls

Stride Access Patterns

Sequential Access - accessing memory in sequential order (contiguous addresses)

QUESTION: Why is sequential access desirable?
Accessing memory has high locality because it becomes very easy to predict the location of the next memory access

Stride-k Access **-** accessing every k-th memory address. Note that stride-1 access patterns is the same as sequential access.

QUESTION: Where might we see stride access patterns?

- Basic matrix multiplication algorithm: multiplying rows of a matrix by the column of the other matrix. Accessing the entries of a column sequentially requires a stride-NUMROWS access pattern.
- Other algorithms involving iterating over columns of matrices, such as image processing

QUESTION: What are the stride patterns of the functions below? How would your order these functions from that which displays the highest locality to that which displays the least?

```
#define N 1000
typedef struct {
  int vel[3];
  int acc[3];
```

```
} point;
point p[N];

void clear1(point* p, int n) {
  int i, j;
  for (i = 0; i < n; i++) {
    for (j = 0; j < 3; j++)
      p[i].vel[j] = 0;
    for (j = 0; j < 3; j++)
      p[i].acc[j] = 0;
  }
}

void clear2(point* p, int n) {
  int i, j;
  for (i = 0; i < n; i++) {
    for (j = 0; j < 3; j++) {
      p[i].vel[j] = 0;
      p[i].acc[j] = 0;
    }
  }
}

void clear3(point* p, int n) {
  int i, j;
  for (j = 0; j < 3; j++) {
    for (i = 0; i < n; i++)
      p[i].vel[j] = 0;
    for (i = 0; i < n; i++)
      p[i].acc[j] = 0;
  }
}
```

Function clear1 accesses the array using a stride-1 reference pattern so it has the best spatial locality. Function clear2 scans each of the N structs in order, but within each struct it hops around, so it has worse spatial locality than clear1. Function clear3 hops around within each struct, but also hops from struct to struct, so clear3 exhibits the worst spatial locality of the three functions.

In `r06-stridebyte.c` and `r07-strideblock.c`, instead of accessing memory sequentially, we use a stride-(1 MB) access pattern.

QUESTION: Why is reading initially slow, and why does it eventually speed up?

- kernel starts caching more and more of the file into memory, speeding up memory accesses

In `r08-stridestdiobyte.c` and `r09-stridestdioblock.c`, we replace the read system calls with calls to fread, and we noticed that the resulting code was much slower.

QUESTION: Why is reading much slower using stdio?

- stdio only keeps a cache of 1 page size
- every time we perform a read, we prefetch data that we end up not using
    - we get cache misses
    - prefetching does not help us, instead it causes ***thrashing***

Thrashing - excessive swapping of pages of data between memory and the hard disk. Often happens when the m emory is full and there is poor locality in the program design.