CS 61C:
Great Ideas in Computer Architecture
More Memory:
Set Associative Caches + Dynamic Memory

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http://inst.eecs.Berkeley.edu/~cs61c/fa13

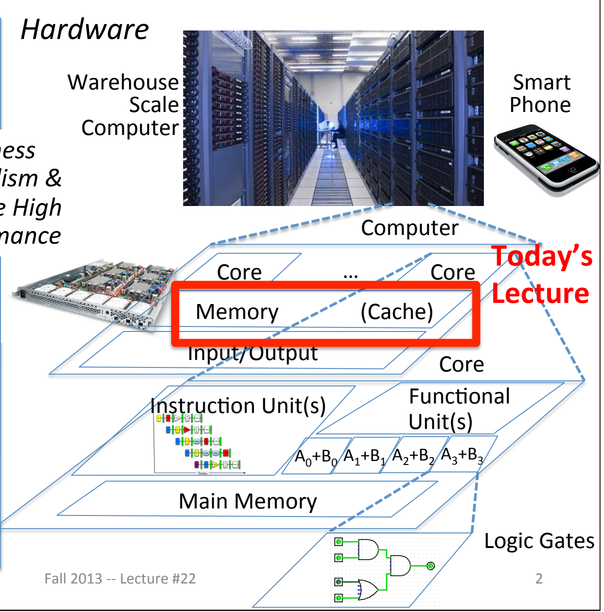
You Are Here!

Software

- Parallel Requests
  Assigned to computer
  e.g., Search "Katz"
- Parallel Threads
  Assigned to core
  e.g., Lookup, Ads
- Parallel Instructions
  >1 instruction @ one time
  e.g., 5 pipelined instructions
- Parallel Data
  >1 data item @ one time
  e.g., Add of 4 pairs of words
- Hardware descriptions
  All gates @ one time
- Programming Languages

Harness Parallelism & Achieve High Performance

Hardware

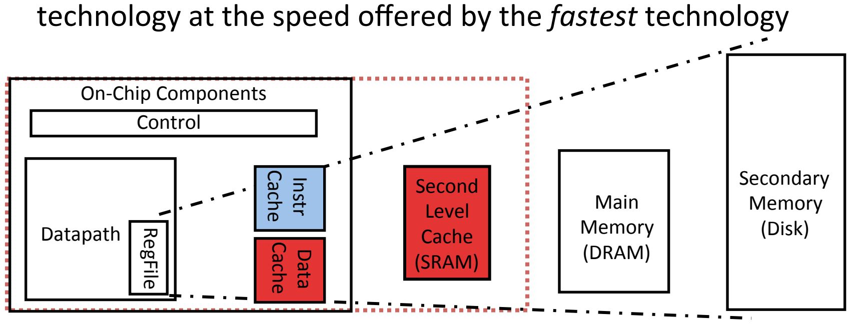


Agenda

- Cache Memory Review
- Set-Associative Caches
- Dynamic Memory

Review: Memory Hierarchy

- Take advantage of the principle of locality to present the user with as much memory as is available in the *cheapest* technology at the speed offered by the *fastest* technology



Speed (cycles):	½'s	1's	10's	100's	10,000's
Size (bytes):	100's	10K's	M's	G's	T's
Cost:	highest				lowest

Review: Cache Performance and Average Memory Access Time (AMAT)

- CPU time = IC × CPI × CC
  $= IC \times \underbrace{(CPI_{ideal} + \text{Memory-stall cycles})}_{CPI_{stall}} \times CC$

  Memory-stall cycles = Read-stall cycles + Write-stall cycles

  Read-stall cycles = reads/program × read miss rate × read miss penalty

  Write-stall cycles = (writes/program × write miss rate × write miss penalty)

  \+ *write buffer stalls*
- AMAT is the average time to access memory considering both hits and misses

  AMAT = Time for a hit + Miss rate x Miss penalty

Improving Cache Performance

- Reduce the time to hit in the cache
  - E.g., Smaller cache, direct-mapped cache, special tricks for handling writes
- *Reduce the miss rate*
  - E.g., Bigger cache, larger blocks
  - *More flexible placement (increase associativity)*
- Reduce the miss penalty
  - E.g., Smaller blocks or critical word first in large blocks, special tricks for handling writes, faster/higher bandwidth memories
  - Use multiple cache levels

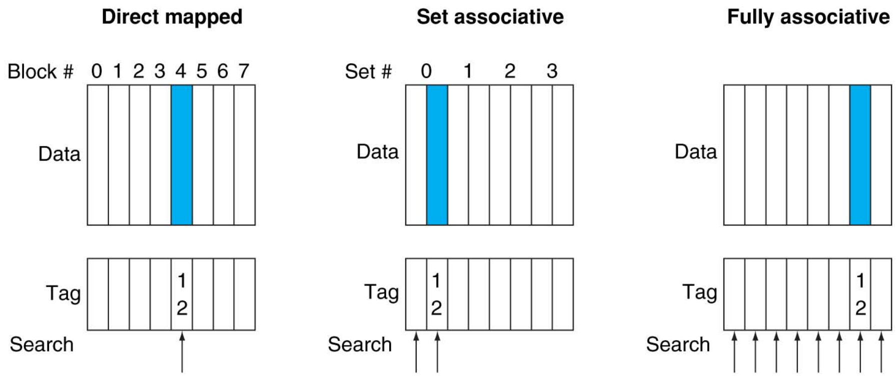
Sources of Cache Misses: The 3Cs

- Compulsory (cold start or process migration, 1st reference):
  - First access to block impossible to avoid; small effect for long running programs
  - Solution: increase block size (increases miss penalty; very large blocks could increase miss rate)
- Capacity:
  - Cache cannot contain all blocks accessed by the program
  - Solution: increase cache size (may increase access time)
- *Conflict (collision):*
  - *Multiple memory locations mapped to the same cache location*
  - *Solution 1: increase cache size*
  - *Solution 2: increase associativity (may increase access time)*

Reducing Cache Misses

- Allow more flexible block placement
- *Direct mapped $*: memory block maps to exactly one cache block
- *Fully associative $*: allow a memory block to be mapped to any cache block
- Compromise: divide $ into sets, each of which consists of n "ways" (*n-way set associative*) to place memory block
  - Memory block maps to unique set determined by index field and is placed in any of the n-ways of that set
  - Calculation: (block address) modulo (# sets in the cache)

Alternative Block Placement Schemes



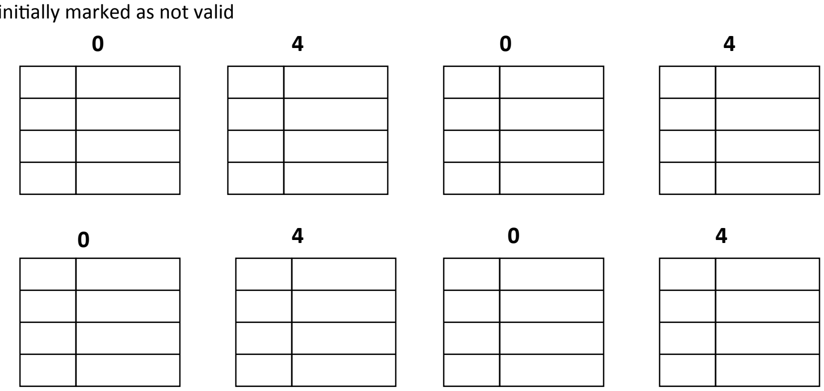
- DM placement: mem block 12 in 8 block cache: only one cache block where mem block 12 can be found—(12 modulo 8) = 4
- SA placement: four sets x 2-ways (8 cache blocks), memory block 12 in set (12 mod 4) = 0; either element of the set
- FA placement: mem block 12 can appear in any cache blocks

Example: 4-Word Direct-Mapped $ Worst-Case Reference String

- Consider the main memory word reference string

Start with an empty cache - all blocks initially marked as not valid

0 4 0 4 0 4 0 4



Example: 4-Word Direct-Mapped $ Worst-Case Reference String

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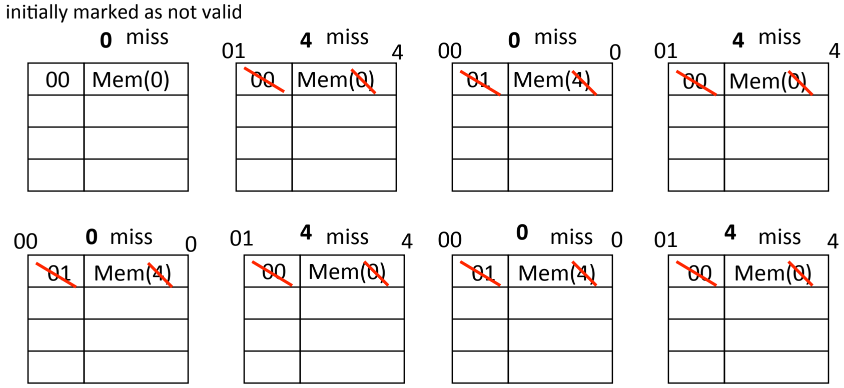
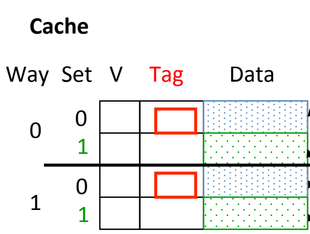
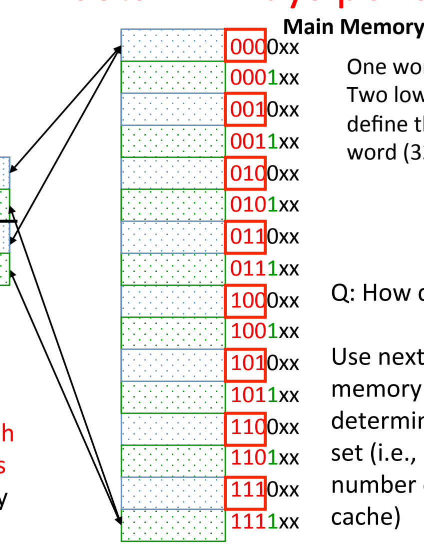


- 8 requests, 8 misses
- Ping pong effect due to conflict misses - two memory locations that map into the same cache block

Example: 2-Way Set Associative $ (4 words = 2 sets x 2 ways per set)





One word blocks
Two low order bits define the byte in the word (32b words)

Q: Is it there?

Compare *all* the cache tags in the set to the high order 3 memory address bits to tell if the memory block is in the cache

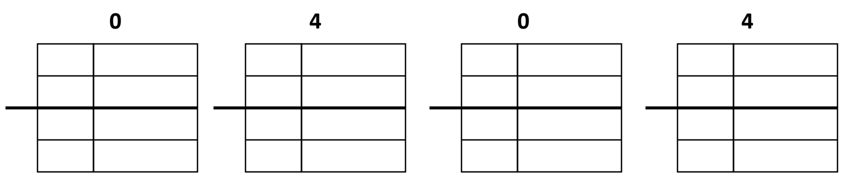
Q: How do we find it?

Use next 1 low order memory address bit to determine which cache set (i.e., modulo the number of sets in the cache)

Example: 4 Word 2-Way SA $ Same Reference String

- Consider the main memory word reference string

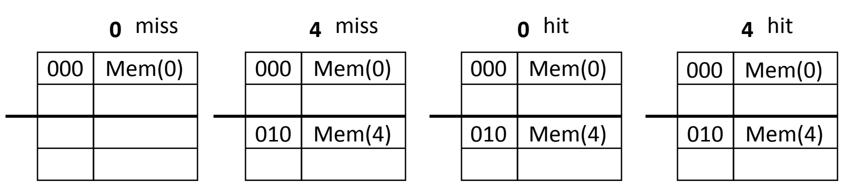
Start with an empty cache - all blocks initially marked as not valid 0 4 0 4 0 4 0 4



Example: 4-Word 2-Way SA $ Same Reference String

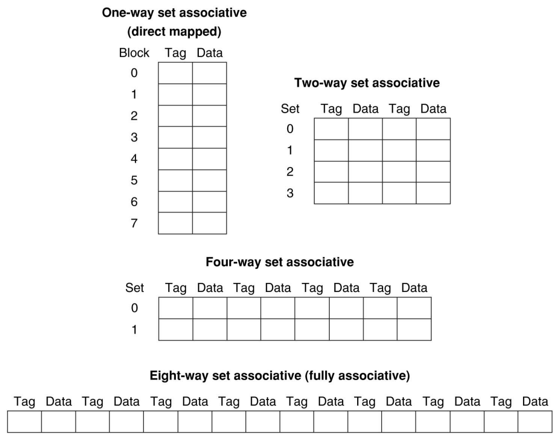
- Consider the main memory word reference string

Start with an empty cache - all blocks initially marked as not valid 0 4 0 4 0 4 0 4



  - 8 requests, 2 misses
- Solves the ping pong effect in a direct mapped cache due to conflict misses since now two memory locations that map into the same cache set can co-exist!

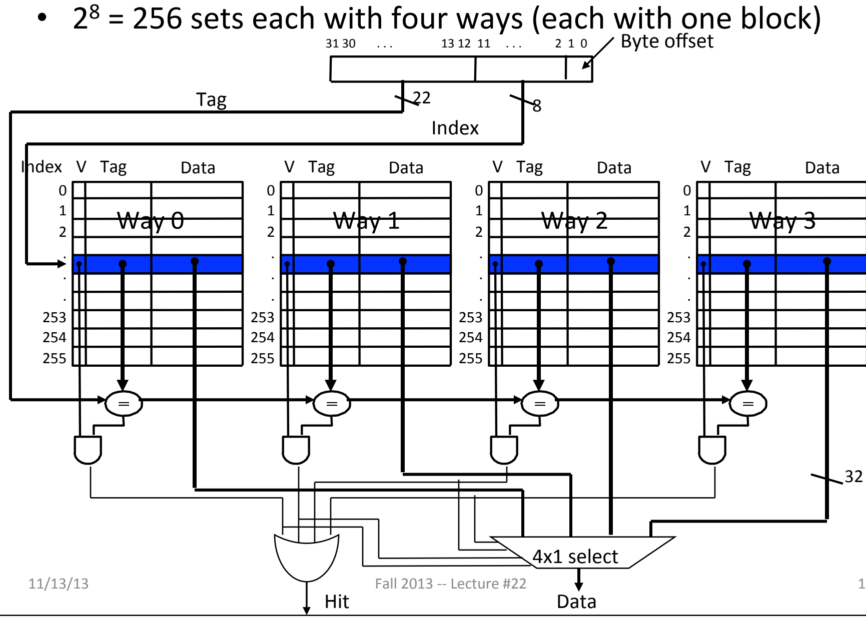
Example: Eight-Block Cache with Different Organizations



Total size of $ in blocks is equal to *number of sets* x *associativity*. For fixed $ size, increasing associativity decreases number of sets while increasing number of elements per set. With eight blocks, an 8-way set-associative $ is same as a fully associative $.

Four-Way Set-Associative Cache

- 2^8 = 256 sets each with four ways (each with one block)



Flashcard Quiz: For fixed capacity and fixed block size, how does increasing associativity effect AMAT?

Increases hit time, decreases miss rate
Decreases hit time, decreases miss rate
Increases hit time, increases miss rate
Decreases hit time, increases miss rate

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Range of Set-Associative Caches

- For a fixed-size cache, each increase by a factor of two in associativity doubles the number of blocks per set (i.e., the number or ways) and halves the number of sets – decreases the size of the index by 1 bit and increases the size of the tag by 1 bit

Tag	Index	Block offset	Byte offset

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Range of Set-Associative Caches

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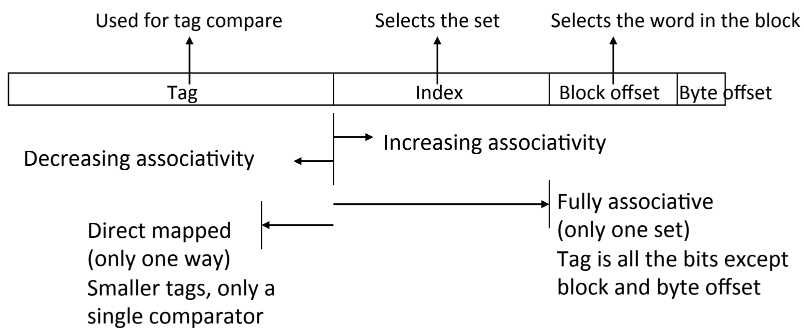
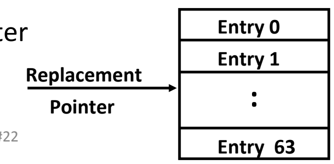


Costs of Set-Associative Caches

- When miss occurs, which way's block selected for replacement?
  - Least Recently Used (LRU): one that has been unused the longest
    - Must track when each way's block was used relative to other blocks in the set
    - For 2-way SA $, one bit per set → set to 1 when a block is referenced; reset the other way's bit (i.e., "last used")
- N-way set-associative cache costs
  - N comparators (delay and area)
  - MUX delay (set selection) before data is available
  - Data available after set selection (and Hit/Miss decision). DM $: block is available before the Hit/Miss decision
    - In Set-Associative, not possible to just assume a hit and continue and recover later if it was a miss

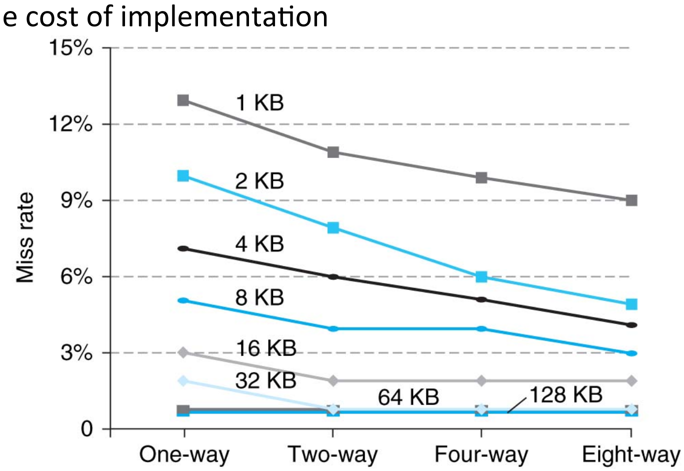
Cache Block Replacement Policies

- Random Replacement
  – Hardware randomly selects a cache item and throw it out
- Least Recently Used
  – Hardware keeps track of access history
  – Replace the entry that has not been used for the longest time
  – For 2-way set-associative cache, need one bit for LRU replacement
- Example of a Simple "Pseudo" LRU Implementation
  – Assume 64 Fully Associative entries
  – Hardware replacement pointer points to one cache entry
  – Whenever access is made to the entry the pointer points to:
    - Move the pointer to the next entry
  – Otherwise: do not move the pointer



Benefits of Set-Associative Caches

- Choice of DM $ or SA $ depends on the cost of a miss versus the cost of implementation

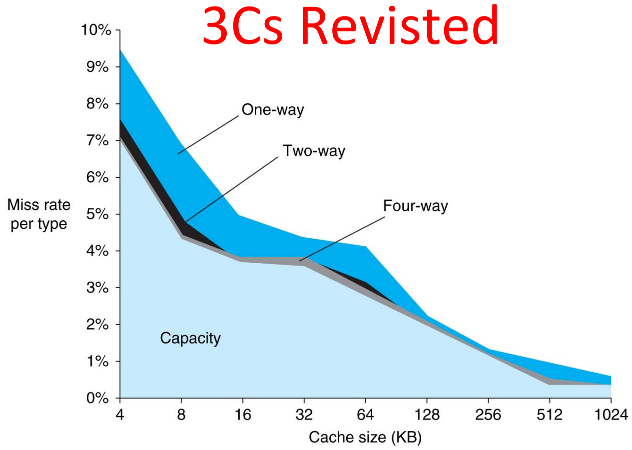


- Largest gains are in going from direct mapped to 2-way (20%+ reduction in miss rate)

How to Calculate 3C's using Cache Simulator

1. *Compulsory*: set cache size to infinity and fully associative, and count number of misses
2. *Capacity*: Change cache size from infinity, usually in powers of 2, and count misses for each reduction in size
   – 16 MB, 8 MB, 4 MB, … 128 KB, 64 KB, 16 KB
3. *Conflict*: Change from fully associative to n-way set associative while counting misses
   – Fully associative, 16-way, 8-way, 4-way, 2-way, 1-way

3Cs Revisted



- Three sources of misses (SPEC2000 integer and floating-point benchmarks)
  – Compulsory misses 0.006%; not visible
  – Capacity misses, function of cache size
  – Conflict portion depends on associativity and cache size

Improving Cache Performance

- Reduce the time to hit in the cache
  - E.g., Smaller cache, direct-mapped cache, special tricks for handling writes
- *Reduce the miss rate*
  - *E.g., Bigger cache, larger blocks*
  - *More flexible placement (increase associativity)*
- *Reduce the miss penalty*
  - *E.g., Smaller blocks or critical word first in large blocks, special tricks for handling for writes, faster/ higher bandwidth memories*
  - *Use multiple cache levels*

Reduce AMAT

- Use multiple levels of cache
- As technology advances, more room on IC die for larger L1$ or for additional levels of cache (e.g., L2$ and L3$)
- Normally the higher cache levels are unified, holding both instructions and data

Design Considerations

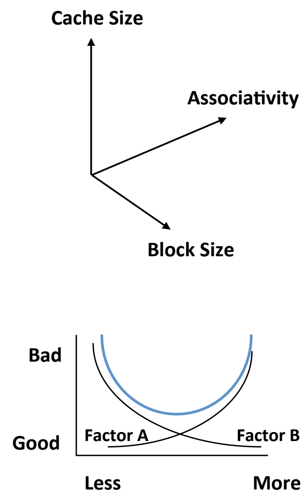
- Different design considerations for L1$ and L2$
  - L1$ focuses on fast access: minimize hit time to achieve shorter clock cycle, e.g., smaller $
  - L2$, L3$ focus on low miss rate: reduce penalty of long main memory access times: e.g., Larger $ with larger block sizes/ higher levels of associativity
- Miss penalty of L1$ is significantly reduced by presence of L2$, so can be smaller/faster even with higher miss rate
- For the L2$, fast hit time is less important than low miss rate
  - L2$ hit time determines L1$'s miss penalty
  - L2$ local miss rate >> than the global miss rate

Flashcard Quiz: In a machine with two levels of cache, what effect does increasing L1 capacity have on L2*?

Decreases L2 capacity misses
Increases L2 local miss rate
Decreases L2 compulsory misses
Decreases L2 global miss rate

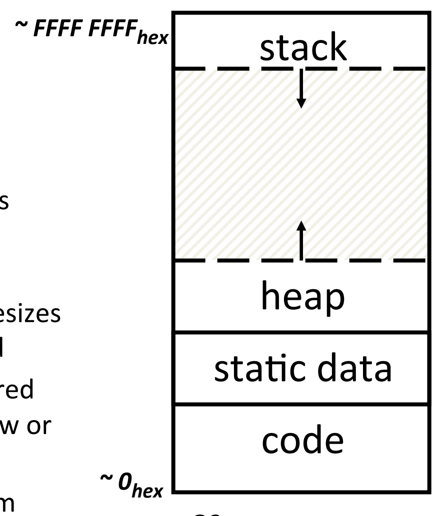
Cache Design Space

- Several interacting dimensions
  - Cache size
  - Block size
  - Associativity
  - Replacement policy
  - Write-through vs. write-back
  - Write allocation
- Optimal choice is a compromise
  - Depends on access characteristics
    - Workload
    - Use (I-cache, D-cache)
  - Depends on technology / cost
- Simplicity often wins



Recap: C Memory Management

- Program's *address space* contains 4 regions:
  - stack: local variables, grows downward
  - heap: space requested for pointers via `malloc()`; resizes dynamically, grows upward
  - static data: variables declared outside main, does not grow or shrink
  - code: loaded when program starts, does not change



OS prevents accesses between stack and heap (via virtual memory)

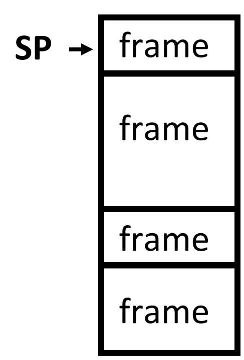
Recap: Where are Variables Allocated?

- If declared outside a procedure, allocated in "static" storage
- If declared inside procedure, allocated on the "stack" and freed when procedure returns
  – main() is treated like a procedure

```
int myGlobal;
main() {
  int myTemp;
}
```


Recap: The Stack

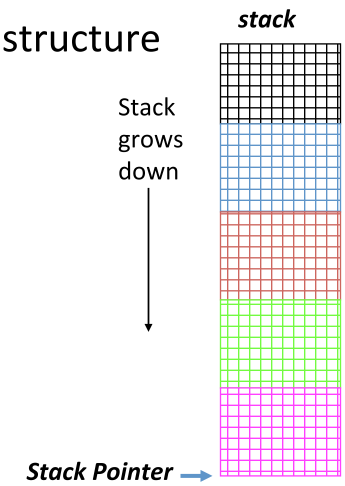
- Stack frame includes:
  – Return "instruction" address
  – Parameters
  – Space for other local variables
- Stack frames contiguous blocks of memory; stack pointer indicates top of stack frame
- When procedure ends, stack frame is tossed off the stack; frees memory for future stack frames



Recap: The Stack

- Last In, First Out (LIFO) data structure

```
main ()
{ a(0);
}
  void a (int m)
  { b(1);
  }
    void b (int n)
    { c(2);
    }
      void c (int o)
      { d(3);
      } void d (int p)
        {
        }
```



Observations

- Code, Static storage are easy: they never grow or shrink
- Stack space is relatively easy: stack frames are created and destroyed in last-in, first-out (LIFO) order
- *Managing the heap is tricky*: memory can be allocated / deallocated at any time

Managing the Heap

- C supports five functions for heap management: **`malloc()`**, `calloc()`, **`free()`**, `cfree()`, `realloc()`
- `malloc(n)`:
  - Allocate a block of uninitialized memory
  - NOTE: Subsequent calls need not yield blocks in continuous sequence
  - `n` is an integer, indicating size of allocated memory block in bytes
  - `sizeof` determines size of given type in bytes, produces more portable code
  - Returns a pointer to that memory location; NULL return indicates no more memory
  - Think of ptr as a *handle* that also describes the allocated block of memory; Additional control information stored in the heap around the allocated block!
- Example:

```
int *ip;
ip = malloc(sizeof(int));

struct treeNode *tp;
tp = malloc(sizeof(struct treeNode));
```


Managing the Heap

- `free(p)`:
  - Releases memory allocated by `malloc()`
  - `p` is pointer containing the address *originally* returned by `malloc()`

```
int *ip;
ip = malloc(sizeof(int));
... .. ..
free(ip);   /* Can you free(ip) after ip++ ? */

struct treeNode *tp;
tp = malloc(sizeof(struct treeNode));
    ... .. ..
free(tp);
```

  - When insufficient free memory, `malloc()` returns `NULL` pointer; **Check for it!**

```
if ((ip = malloc(sizeof(int))) == NULL){
    printf("\nMemory is FULL\n");
    exit(1);
}
```

  - When you free memory, you must be sure that you pass the **original address** returned from `malloc()` to `free()`; Otherwise, system exception (or worse)!

Common Memory Problems

- Using uninitialized values
- Using memory that you don't own
  - Deallocated stack or heap variable
  - Out-of-bounds reference to stack or heap array
  - Using NULL or garbage data as a pointer
- Improper use of free/realloc by messing with the pointer handle returned by malloc/calloc
- Memory leaks (you allocated something you forgot to later free)

Memory Debugging Tools

- Runtime analysis tools for finding memory errors
  - Dynamic analysis tool: collects information on memory management while program runs
  - Contrast with static analysis tool like `lint`, which analyzes source code without compiling or executing it
  - No tool is guaranteed to find ALL memory bugs – this is a very challenging programming language research problem
  - Runs 10X slower

http://valgrind.org

Using Memory You Don't Own

- What is wrong with this code?

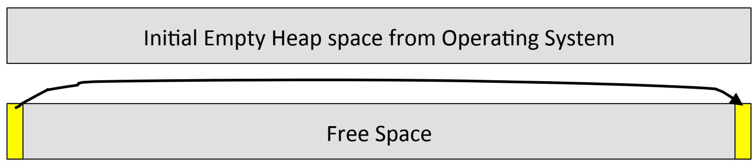
```
int *ipr, *ipw;
void ReadMem() {
      int i, j;
      *ipr = malloc(4 * sizeof(int));
       i = *(ipr - 1000); j = *(ipr + 1000);
      free(ipr);
   }

   void WriteMem() {
      *ipw = malloc(5 * sizeof(int));
      *(ipw - 1000) = 0; *(ipw + 1000) = 0;
      free(ipw);
   }
```


How are Malloc/Free implemented?

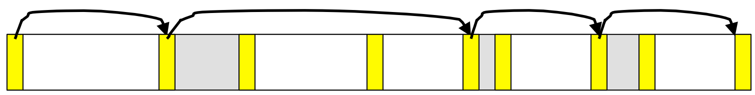
- Underlying operating system allows malloc library to ask for large blocks of memory to use in heap (e.g., using Unix sbrk() call)
- C Malloc library creates data structure inside unused portions to track free space

Simple Slow Malloc Implementation



Malloc library creates linked list of empty blocks (one block initially)

First allocation chews up space from start of free space

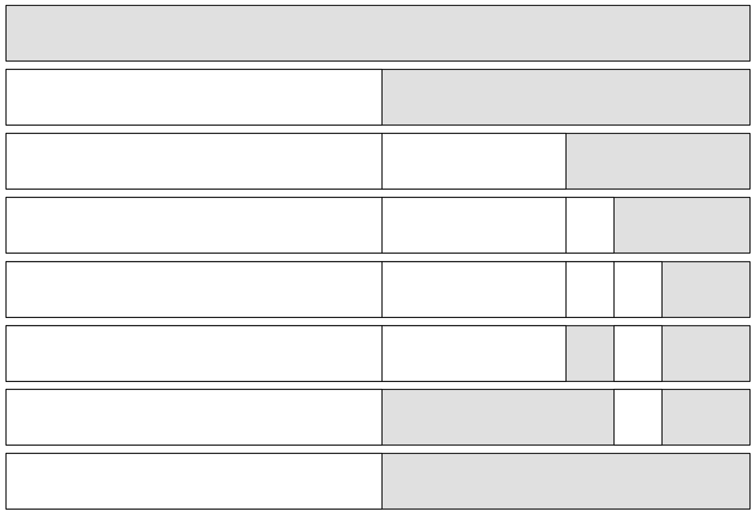


After many mallocs and frees, have potentially long linked list of odd-sized blocks
Frees link block back onto linked list – might merge with neighboring free space

Faster malloc implementations

- Keep separate pools of blocks for different sized objects
- "Buddy allocators" always round up to power-of-2 sized chunks to simplify finding correct size and merging neighboring blocks:

Power-of-2 "Buddy Allocator"



Malloc Implementations

- All provide the same library interface, but can have radically different implementations
- Uses headers at start of allocated blocks and space in unallocated memory to hold malloc's internal data structures
- Rely on programmer remembering to free with same pointer returned by alloc
- Rely on programmer not messing with internal data structures accidentally!

Faulty Heap Management

- What is wrong with this code?

```
int *pi;
void foo() {
  pi = malloc(8*sizeof(int));
  …
  free(pi);
}

void main() {
  pi = malloc(4*sizeof(int));
  foo();
  …
}
```


Faulty Heap Management

- What is wrong with this code?

```
int *plk = NULL;
void genPLK() {
  plk = malloc(2 * sizeof(int));
  … … …
  plk++;
}
```

Faulty Heap Management

- What is wrong with this code?

```
void FreeMemX() {
  int fnh = 0;
  free(&fnh);
}

void FreeMemY() {
  int *fum = malloc(4 * sizeof(int));
  free(fum+1);
  free(fum);
  free(fum);
}
```


Using Memory You Haven't Allocated

- What is wrong with this code?

```
void StringManipulate() {
  const char *name = "Safety Critical";
  char *str = malloc(10);
  strncpy(str, name, 10);
  str[10] = '\0';
  printf("%s\n", str);
}
```

Using Memory You Don't Own

- What's wrong with this code?

```
char *append(const char* s1, const char *s2) {
  const int MAXSIZE = 128;
  char result[128];
  int i=0, j=0;
  for (j=0; i<MAXSIZE-1 && j<strlen(s1); i++,j++) {
   result[i] = s1[j];
  }
  for (j=0; i<MAXSIZE-1 && j<strlen(s2); i++,j++) {
   result[i] = s2[j];
  }
  result[++i] = '\0';
  return result;
}
```


Using Memory You Don't Own

- What is wrong with this code?

```
typedef struct node {
    struct node* next;
    int val;
} Node;

int findLastNodeValue(Node* head) {
    while (head->next != NULL) {
       head = head->next;
    }
    return head->val;
}
```

Managing the Heap

- `calloc(n, size)`:
  - Allocate n elements of same data type; n can be an integer variable, use `calloc()` to allocate a dynamically size array
  - `n` is the # of array elements to be allocated
  - `size` is the number of bytes of each element
  - `calloc()` guarantees that the memory contents are initialized to zero

  E.g.: allocate an array of 10 elements

  ```
  int *ip;
  ip = calloc(10, sizeof(int));
  ```

  `*(ip+1)` refers to the 2nd element, like `ip[1]`

  `*(ip+i)` refers to the i+1th element, like `ip[i]`

  Beware of referencing beyond the allocated block: e.g., `*(ip+10)`

  - `calloc()` returns `NULL` if no further memory is available
- `cfree(p) // Legacy function – same as free`
  - `cfree()` releases the memory allocated by `calloc()`; E.g.: `cfree(ip);`

Managing the Heap

- `realloc(p,size)`:
  - Resize a previously allocated block at `p` to a new `size`
  - If `p` is `NULL`, then `realloc` behaves like `malloc`
  - If `size` is 0, then `realloc` behaves like `free`, deallocating the block from the heap
  - Returns new address of the memory block; NOTE: it is likely to have moved!

  E.g.: allocate an array of 10 elements, expand to 20 elements later

  ```
  int *ip;
  ip = malloc(10*sizeof(int));
  /* always check for ip == NULL */
  … … …
  ip = realloc(ip,20*sizeof(int));
  /* always check for ip == NULL */
  /* contents of first 10 elements retained */
  … … …
  realloc(ip,0); /* identical to free(ip) */
  ```

Using Memory You Don't Own

- What is wrong with this code?

```
int* init_array(int *ptr, int new_size) {
  ptr = realloc(ptr, new_size*sizeof(int));
  memset(ptr, 0, new_size*sizeof(int));
  return ptr;
}

int* fill_fibonacci(int *fib, int size) {
  int i;
  init_array(fib, size);
  /* fib[0] = 0; */ fib[1] = 1;
  for (i=2; i<size; i++)
   fib[i] = fib[i-1] + fib[i-2];
  return fib;
}
```


And, In Conclusion …

- Name of the Game: Reduce Cache Misses
  - One way to do it: set-associativity
  - N-way Cache of 2^{N+M} blocks: 2^N ways x 2^M sets
  - Multi-level caches: Optimize 1st level to be fast! 2nd and 3rd to minimize memory access penalty
- Dynamic Memory
  - Program Storage + Static storage + Stack Storage
  - *The Heap (dynamic storage):* `malloc()` *and* `free()`
- Common Dynamic Memory Problems
  - Using uninitialized values
  - Accessing memory beyond your allocated region
  - Improper use of free by changing pointer handle returned by malloc
  - Memory leaks: mismatched malloc/free pairs