CS 110
Computer Architecture

Lecture 4: *Introduction to C, Part III*

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http://shtech.org/courses/ca/

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Slides based on UC Berkley's CS61C

Review

- Pointers and arrays are virtually same
- C knows how to increment pointers
- C is an efficient language, with little protection
  - Array bounds not checked
  - Variables not automatically initialized
- Use handles to change pointers
- (Beware) The cost of efficiency is more overhead for the programmer.
  - "C gives you a lot of extra rope but be careful not to hang yourself with it!"

Valid Pointer Arithmetic

- Add an integer to a pointer.
- Subtract 2 pointers (in the same array)
- Compare pointers (<, <=, ==, !=, >, >=)
- Compare pointer to NULL (indicates that the pointer points to nothing)

Everything else illegal since makes no sense:

- adding two pointers
- multiplying pointers
- subtract pointer from integer

Arguments in `main()`

- To get arguments to the main function, use:
  - `int main(int argc, char *argv[])`
- What does this mean?
  - `argc` contains the number of strings on the command line (the executable counts as one, plus one for each argument). Here `argc` is 2:

    sort myFile
  - `argv` is a *pointer* to an array containing the arguments as strings

Example

- `foo hello 87`
- `argc = 3 /* number arguments */`
- `argv[0] = "foo",`
  `argv[1] = "hello",`
  `argv[2] = "87"`
  - Array of pointers to strings

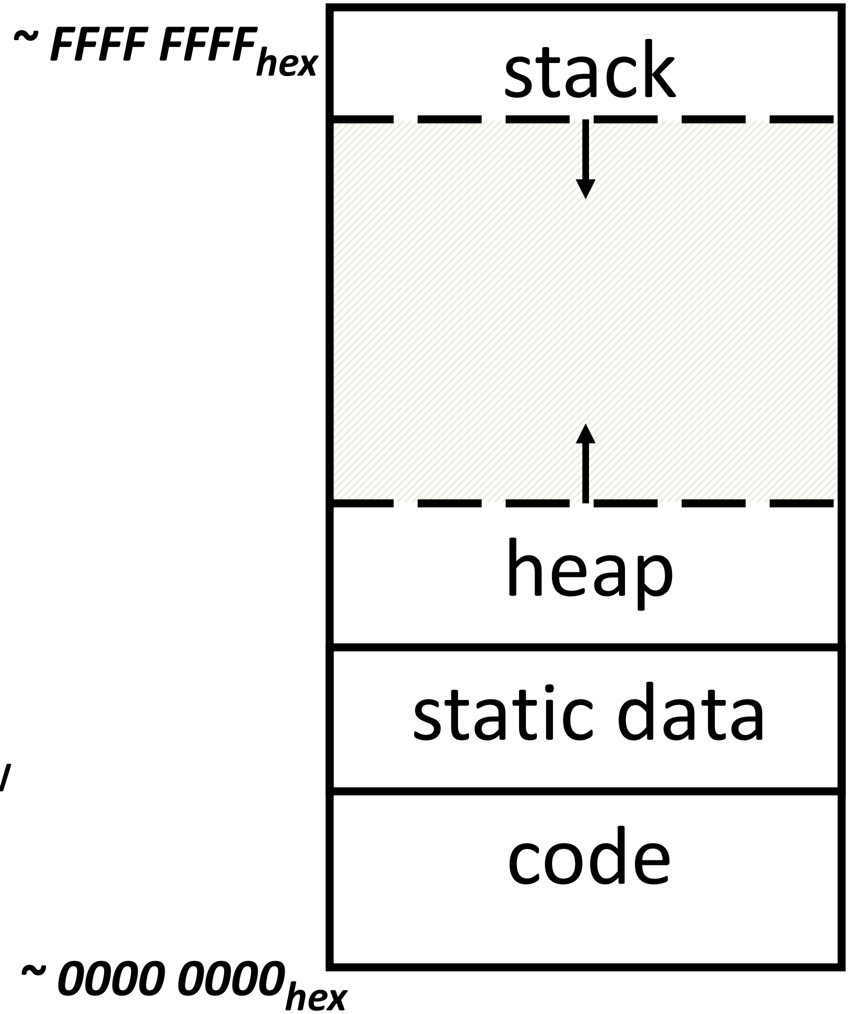
C Memory Management

- How does the C compiler determine where to put all the variables in machine’s memory?
- How to create dynamically sized objects?
- To simplify discussion, we assume one program runs at a time, with access to all of memory.
- Later, we’ll discuss virtual memory, which lets multiple programs all run at same time, each thinking they own all of memory.

C Memory Management

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

Memory Address
(32 bits assumed here)



Where are Variables Allocated?

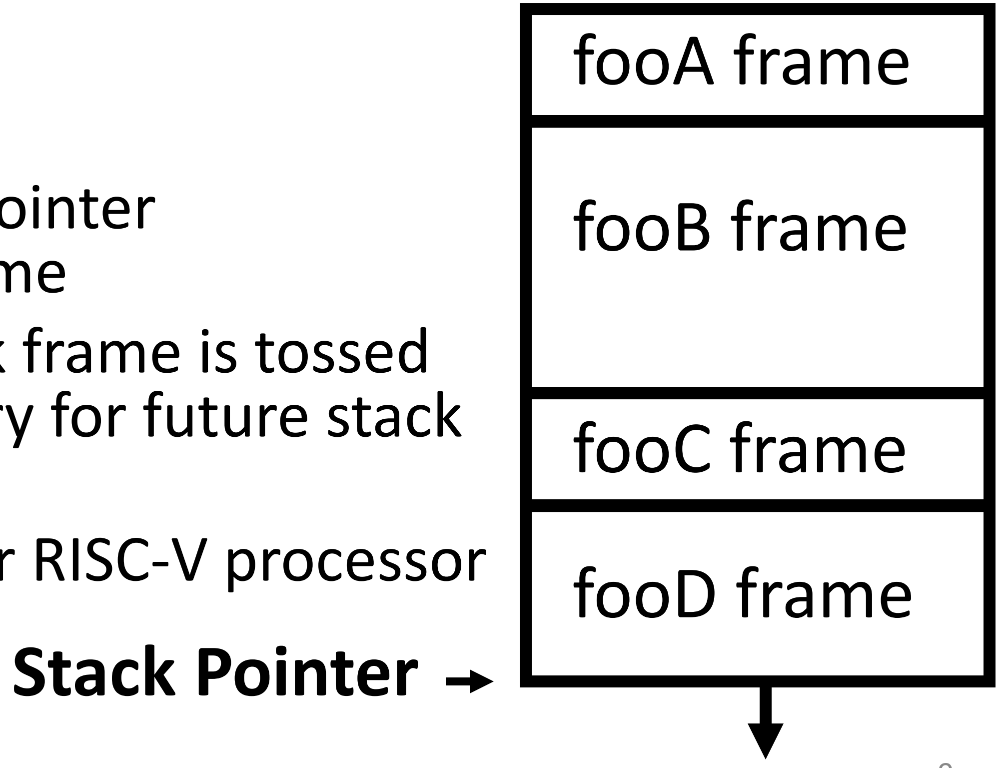
- If declared outside a function, allocated in "static" storage
- If declared inside function, allocated on the "stack" and freed when function returns
  - main() is treated like a function

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

The Stack

- Every time a function is called, a new frame is allocated on the stack
- Stack frame includes:
  - Return address (who called me?)
  - Arguments
  - Space for local variables
- Stack frames contiguous blocks of memory; stack pointer indicates start of stack frame
- When function ends, stack frame is tossed off the stack; frees memory for future stack frames
- We'll cover details later for RISC-V processor

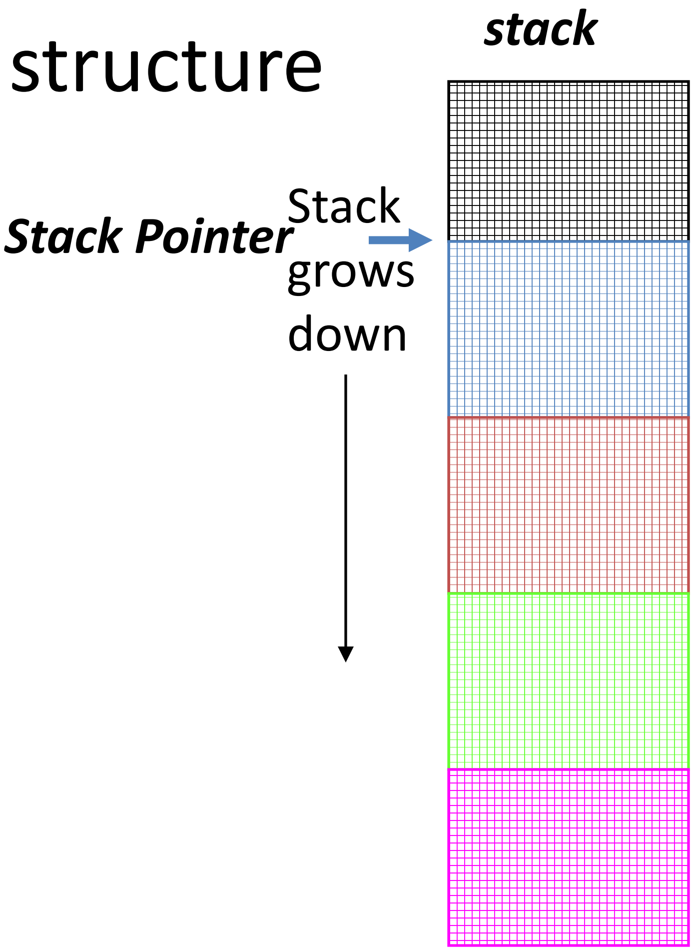
```
fooA() { fooB(); }
fooB() { fooC(); }
fooC() { fooD(); }
```



Stack Animation

- 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)
        {
        }
```



Managing the Heap

C supports five functions for heap management:

- **`malloc()`** allocate a block of uninitialized memory
- **`calloc()`** allocate a block of zeroed memory
- **`free()`** free previously allocated block of memory
- **`realloc()`** change size of previously allocated block
  - careful – it might move!

Malloc()

- `void *malloc(size_t n)`:
  - Allocate a block of uninitialized memory
  - NOTE: Subsequent calls might not yield blocks in contiguous addresses
  - `n` is an integer, indicating size of allocated memory block in bytes
  - `size_t` is an unsigned integer type big enough to "count" memory bytes
  - `sizeof` returns size of given type in bytes, produces more portable code
  - Returns `void*` pointer to block; `NULL` return indicates no more memory
  - Think of pointer as a *handle* that describes the allocated block of memory; Additional control information stored in the heap around the allocated block!
- Examples:

"Cast" operation, changes type of a variable. Here changes ***`(void *)`*** *to* ***`(int *)`***

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

typedef struct { … } TreeNode;
TreeNode *tp = (TreeNode *) malloc(sizeof(TreeNode));
```

Managing the Heap

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

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

typedef struct {… } TreeNode;
TreeNode *tp = (TreeNode *) malloc(sizeof(TreeNode));
    ... .. ..
free((void *) tp);
```

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

```
if ((ip = (int *) malloc(sizeof(int))) == NULL){
    printf("\nMemory is FULL\n");
    exit(1); /* Crash and burn! */
}
```

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

Using Dynamic Memory

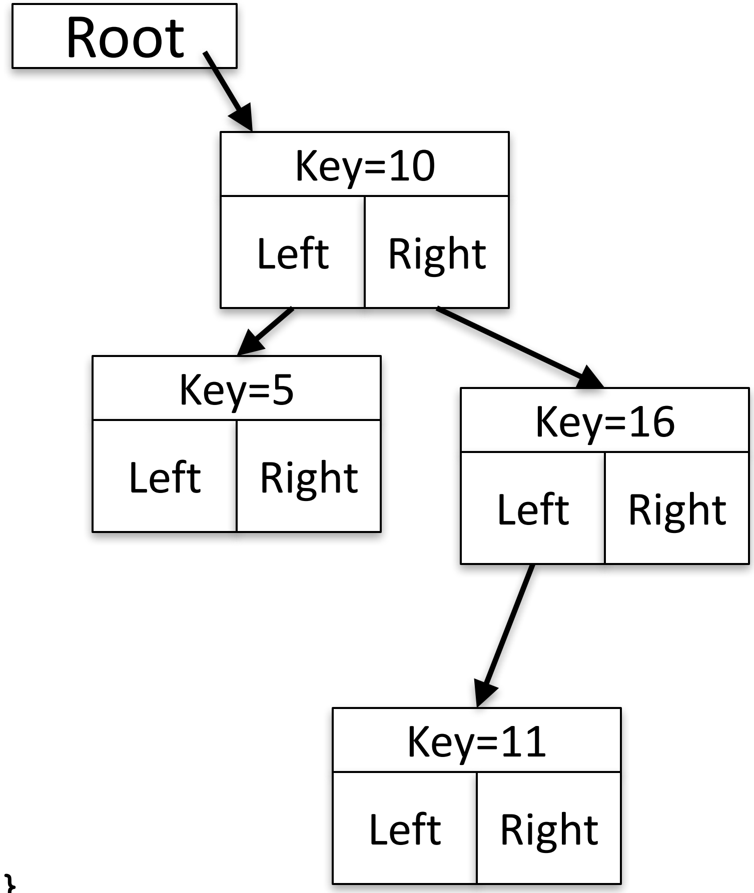
```
typedef struct node {
        int key;
        struct node *left;
        struct node *right;
} Node;

Node *root = 0;

Node *create_node(int key, Node *left, Node *right)
{
   Node *np;
   if ( (np = (Node*) malloc(sizeof(Node))) == NULL)
   { printf("Memory exhausted!\n"); exit(1); }
   else
   {  np->key = key;
      np->left = left;
      np->right = right;
      return np;
   }
}

void insert(int key, Node **tree)
{
   if ( (*tree) == NULL)
   { (*tree) = create_node(key, NULL, NULL); return; }

   if (key <= (*tree)->key)
      insert(key, &((*tree)->left));
   else
      insert(key, &((*tree)->right));
}
```



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

Question!

```
int x = 2;
int result;

int foo(int n)
{   int y;
    if (n <= 0) { printf("End case!\n"); return 0; }
    else
    {  y = n + foo(n-x);
       return y;
    }
}
result = foo(10);
```

Right after the **`printf`** executes but before the **`return 0`**, how many copies of **`x`** and **`y`** are there allocated in memory?

A: #x = 1, #y = 1

B: #x = 1, #y = 5

C: #x = 1, #y = 6

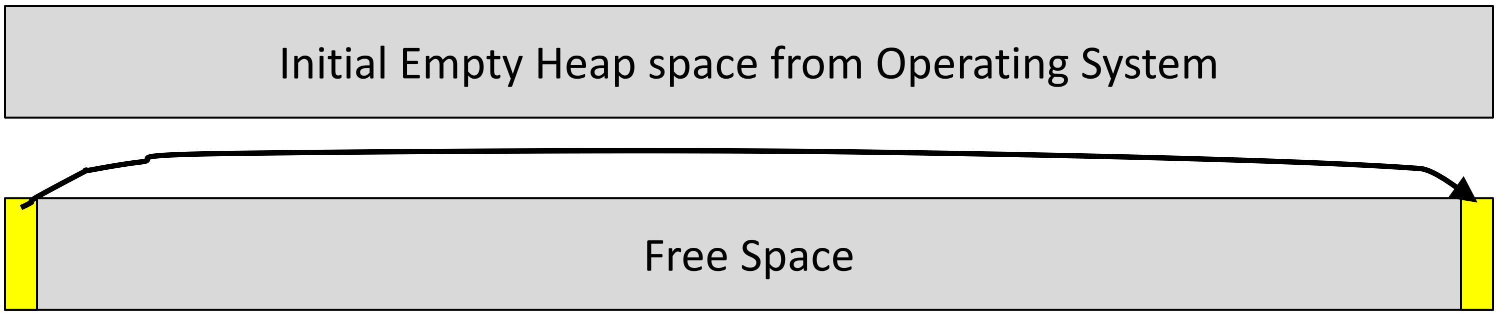
D: #x = 5, #y = 1

E: #x = 6, #y = 6

How are Malloc/Free implemented?

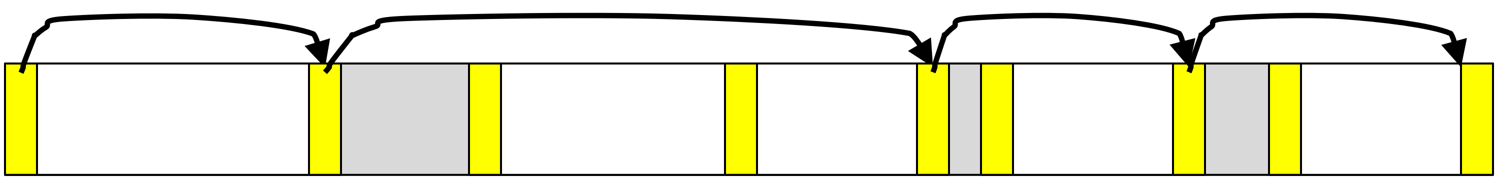
- Underlying operating system allows **`malloc`** library to ask for large blocks of memory to use in heap (e.g., using Unix **`sbrk()`** call)
- C standard **`malloc`** library creates data structure inside unused portions to track free space

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

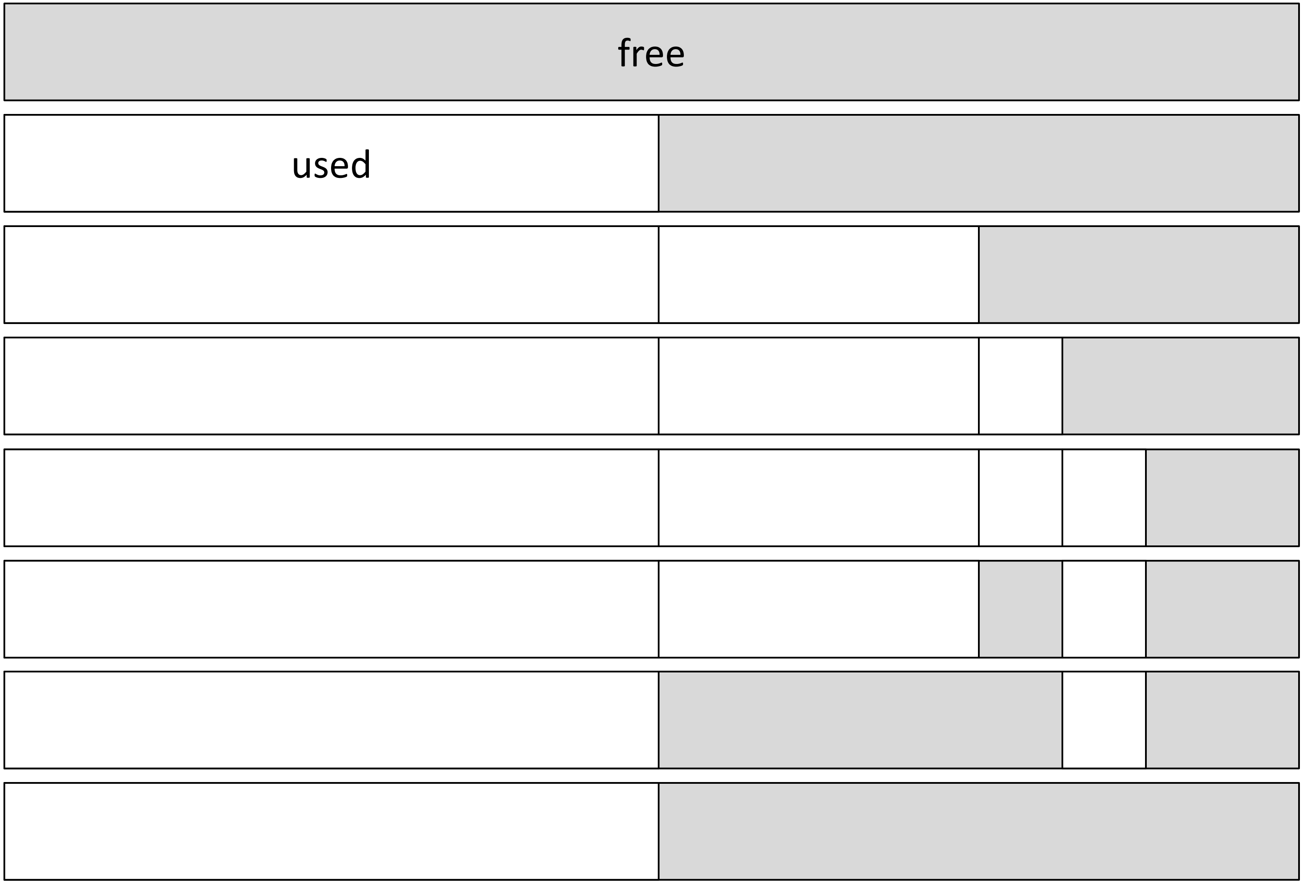


After many mallocs and frees, have potentially long linked list of odd-sized blocks
Frees link block back onto linked list – might merge with neighboring free space

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 **`malloc`**
- Rely on programmer not messing with internal data structures accidentally!

AMD’d current Ryzen 2000 (Zen+)

- AMD’s newest processor
- Ryzen 7 2700X (USD 369):
  - 8 cores with SMT -> 16 threads
  - 3.7GHz (Turbo: 4.35GHz)
  - Cache: L2: 4MB, L3 20MB
  - TDP: 120W
  - 12 nm FinFET
  - Up to 8 channels of DDR4 memory

Extended Frequency Range (XFR)

Rewarding Enthusiast Cooling

- Permits frequencies above and beyond ordinary Precision Boost limits
- Clockspeed scales with cooling solution: air, water, and LN_2
- Fully automated; no user intervention required

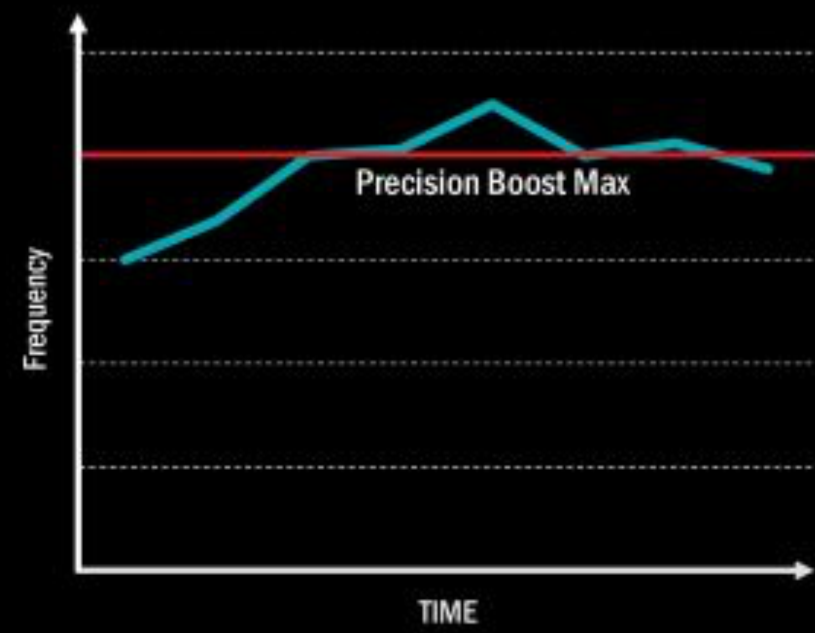


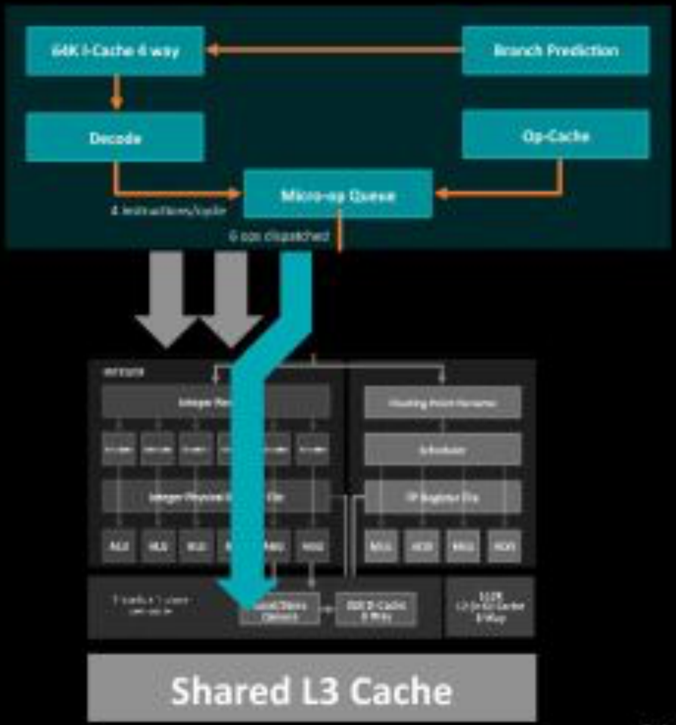
Chart for illustrative purposes only

AMD | ZEN

Neural Net Prediction

Scary Smart Prediction

- A true artificial network inside every "Zen" processor
- Builds a model of the decisions driven by software code execution
- Anticipates future decisions, pre-load instructions, choose the best path through the CPU



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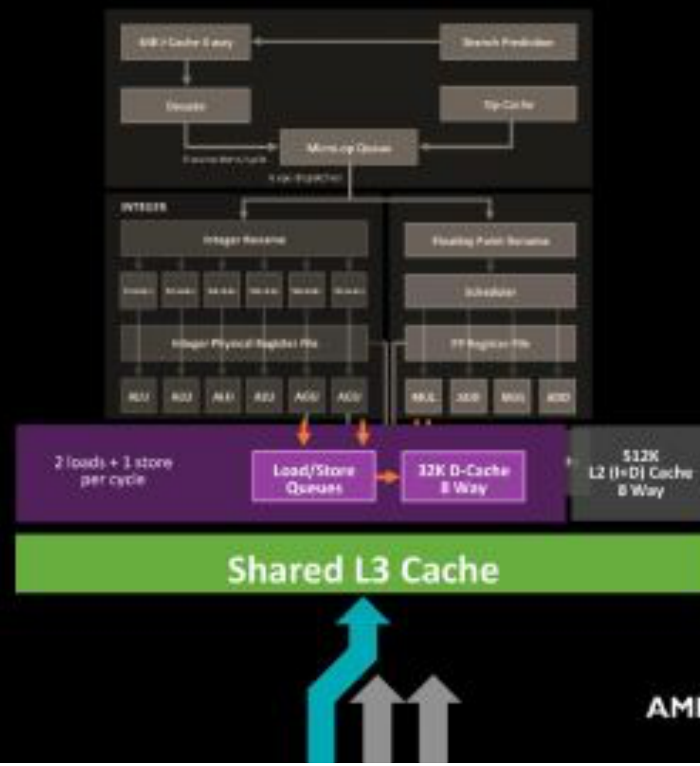
Smart Prefetch

The Right Data At The Right Time

- Anticipates the location of future data accesses by application code
- Sophisticated learning algorithms model and learn application data access patterns
- Prefetches vital data into local cache so it's ready for immediate use



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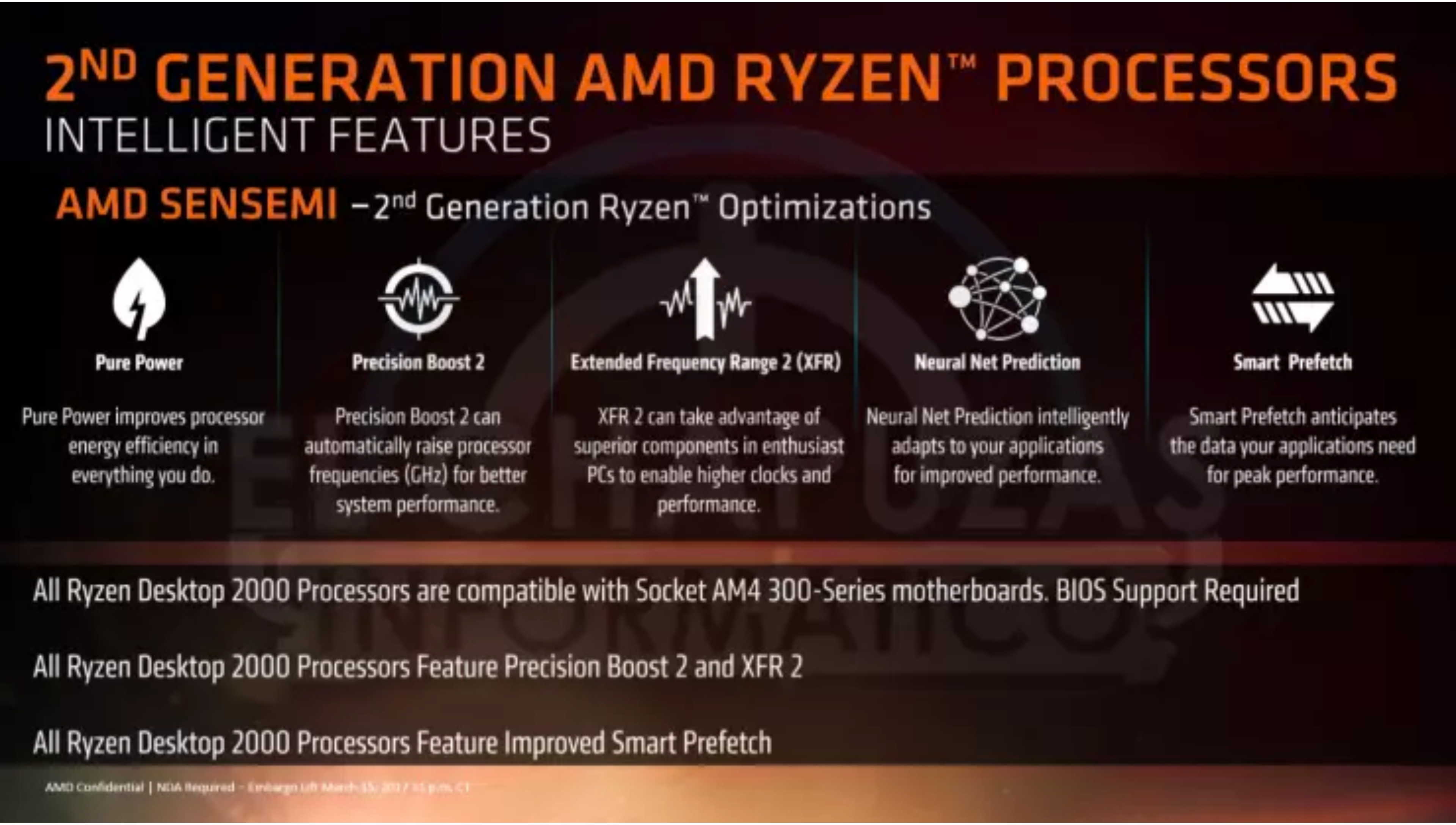
2ND GENERATION AMD RYZEN™ PROCESSORS
INTELLIGENT FEATURES
AMD SENSEMI – 2nd Generation Ryzen™ Optimizations
Pure Power
Pure Power improves processor energy efficiency in everything you do.
Precision Boost 2
Precision Boost 2 can automatically raise processor frequencies (GHz) for better system performance.
Extended Frequency Range 2 (XFR)
XFR 2 can take advantage of superior components in enthusiast PCs to enable higher clocks and performance.
Neural Net Prediction
Neural Net Prediction intelligently adapts to your applications for improved performance.
Smart Prefetch
Smart Prefetch anticipates the data your applications need for peak performance.
All Ryzen Desktop 2000 Processors are compatible with Socket AM4 300-Series motherboards. BIOS Support Required
All Ryzen Desktop 2000 Processors Feature Precision Boost 2 and XFR 2
All Ryzen Desktop 2000 Processors Feature Improved Smart Prefetch

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)

Using Memory You Don't Own

- What is wrong with this code?
- Using pointers beyond the range that had been malloc'd
  - May look obvious, but what if mem refs had been result of pointer arithmetic that erroneously took them out of the allocated range?

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

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

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

- Memory leak: *more mallocs than frees*

```
int *pi;
void foo() {
   pi = malloc(8*sizeof(int));
   /* Allocate memory for pi */
   /* Oops, leaked the old memory pointed to by pi */
   …
   free(pi); /* foo() is done with pi, so free it */
}

void main() {
   pi = malloc(4*sizeof(int));
   foo(); /* Memory leak: foo leaks it */
  …
}
```

Faulty Heap Management

- What is wrong with this code?

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

Faulty Heap Management

- Potential memory leak – handle has been changed, do you still have copy of it that can correctly be used in a later free?

```
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);
}
```

Faulty Heap Management

- Can’t free non-heap memory; Can’t free memory that hasn’t been allocated

```
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 Haven't Allocated

- Reference beyond array bounds

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

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

- Beyond stack read/write

```
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;
}
```

`result` is a local array name – stack memory allocated

Function returns pointer to stack memory – won't be valid after function returns

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;
    }
```

Using Memory You Don't Own

- Following a NULL pointer to mem addr 0!

```
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

- `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 = (int *) malloc(10*sizeof(int));
/* always check for ip == NULL */
… … …
ip = (int *) 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;
}
```

Using Memory You Don't Own

- Improper matched usage of mem handles

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

Remember: `realloc` may move entire block

```
int* fill_fibonacci(int *fib, int size) {
   int i;
   /* oops, forgot: fib = */ 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;
}
```

What if array is moved to new location?

And In Conclusion, …

- All data is in memory
  - Each memory location has an address to use to refer to it and a value stored in it
- Pointer is a C version (abstraction) of a data address
  - `*` "follows" a pointer to its value
  - `&` gets the address of a value
  - Arrays and strings are implemented as variations on pointers
- C is an efficient language, but leaves safety to the programmer
  - Variables not automatically initialized
  - Use pointers with care: they are a common source of bugs in programs

And In Conclusion, …

- C has three main memory segments in which to allocate data:
  - Static Data: Variables outside functions
  - Stack: Variables local to function
  - Heap: Objects explicitly malloc-ed/free-d.
- Heap data is biggest source of bugs in C code