ECE 2400 Computer Systems Programming
Fall 2017

Topic 4: C Pointers

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- Pointers are a way of referring to the location of a variable
- Pointers enable a variable's value to be a "pointer" to a completely different variable
- Programmers can access what a pointer points to and redirect the pointer to point to something else
- This is an example of indirection, a powerful programming concept
- Pointers can be confusing, but the key is to carefully construct the corresponding stack frame diagram

1. Pointer Basics

- Pointers require introducing new types and new operators

- Every type `T` has a corresponding pointer type `T*`
- A variable of type `T*` contains a pointer to a variable of type `T`

```
int*   b_ptr;    // pointer to a variable of type int
char*  a_ptr;    // pointer to a variable of type char
float* c_ptr;    // pointer to a variable of type float
```

- The address-of operator (`&`) evaluates to the location of a variable
- The address-of operator is used to initialize/assign to pointers

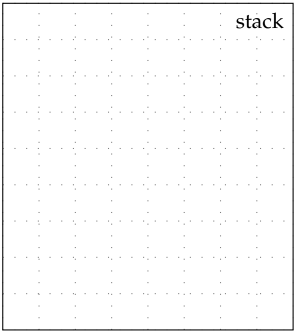
```
int  b;          // variable of type int
int* b_ptr;      // pointer to a variable of type int
b_ptr = &b;      // assign location of b to b_ptr
```

- The dereference operator (`*`) evaluates to the value of the variable the pointer points to

```
int  b = 42;      // initialize variable of type int to 42
int* b_ptr = &b; // pointer to a variable of type int
int  c = *b_ptr; // initialize c with what b_ptr points to
```

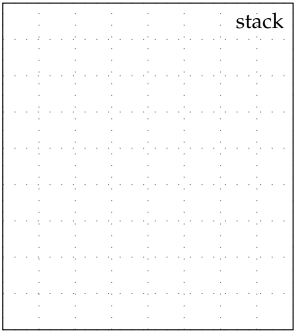
Example declaring, initializing, RHS dereferencing pointers

```
int  a = 3;
int* a_ptr;
a_ptr = &a;

int  b = 2;
int  c = b + (*a_ptr);
```



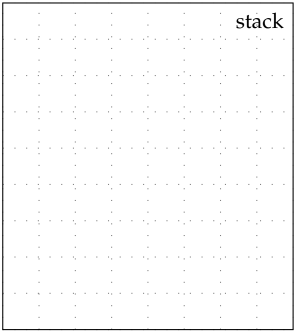
Example illustrating aliasing

```
int  a = 3;
int* a_ptr0 = &a;
int* a_ptr1 = a_ptr0;
int  c = (*a_ptr0) + (*a_ptr1);
```



Example declaring, initializing, LHS dereferencing pointers

```
int  a = 3;
int  b = 2;

int  c;
int* c_ptr = &c;
*c_ptr = a + b;
```

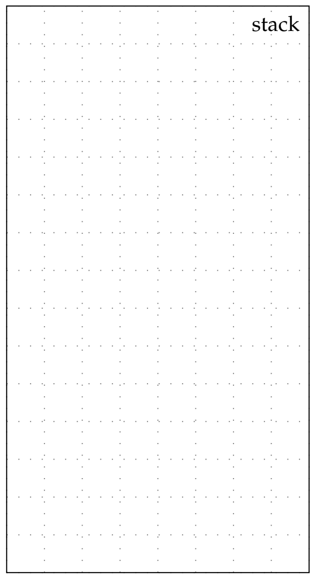


- Be careful – three very different uses of the * symbol!
  - Multiplication operator `int  a = b * c;`
  - Pointer type `int* d = &a;`
  - Dereference operator `int  e = *d;`

2. Call by Value vs. Call by Reference

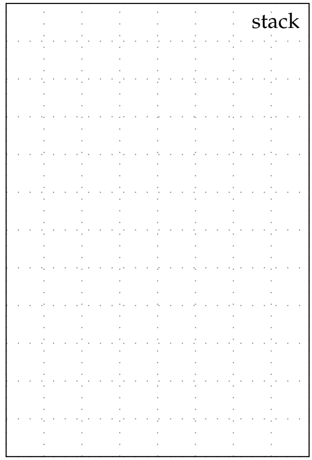
- So far, we have always used call by value
- Call by value *copies* values into parameters
- Changes to parameters by callee *are not seen* by caller

```
void sort( int x, int y )
{
  if ( x > y ) {
    int temp = x;
    x = y;
    y = temp;
  }
}

int main( void )
{
  int a = 9;
  int b = 5;
  sort( a, b );
  return 0;
}
```



- Call by reference uses pointers as parameters
- Callee can read and modify parameters by dereferencing pointers
- Changes to parameters by callee *are seen* by caller

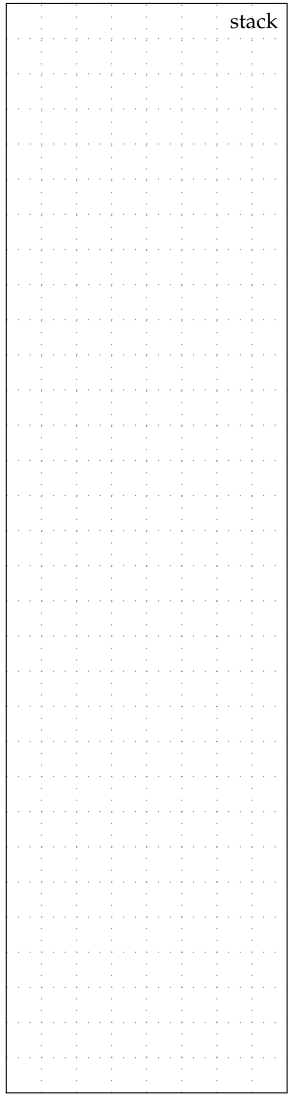
```
void sort( int* x_ptr,
           int* y_ptr )
{
  if ( (*x_ptr) > (*y_ptr) ) {
    int temp = *x_ptr;
    *x_ptr   = *y_ptr;
    *y_ptr   = temp;
  }
}

int main( void )
{
  int a = 9;
  int b = 5;
  sort( &a, &b );
  return 0;
}
```



http://cpp.sh/537og

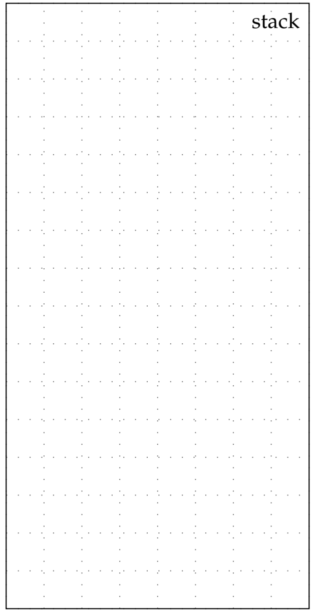
```
void sort3( int* p_ptr,
            int* q_ptr,
            int* r_ptr )
{
  sort( p_ptr, q_ptr );
  sort( q_ptr, r_ptr );
  sort( p_ptr, 1_ptr );
}

int main( void )
{
  int a = 9;
  int b = 5;
  int c = 3;
  sort3( &a, &b, &c );
  return 0;
}
```

http://cpp.sh/77j33



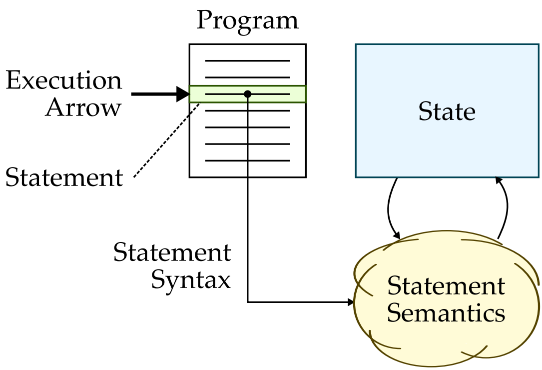
Draw stack frame diagram corresponding to the execution of this program

```c
void avg( int* result_ptr,
          int x, int y )
{
  int sum = x + y;
  *result_ptr = sum / 2;
}

int main( void )
{
  int a = 10;
  int b = 20;
  int c;
  avg( &c, a, b );
  return 0;
}
```



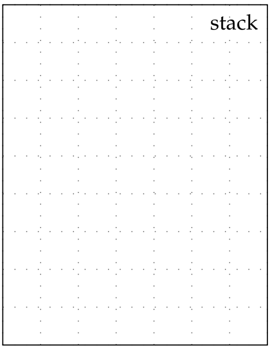
3. Mapping Conceptual Storage to Machine Memory

- Our current use of stack frame diagrams is conceptual
- Real machine uses memory to store variables
- Real machine does not use "arrows", uses memory addresses

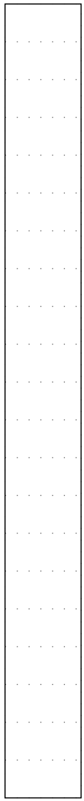


- Can visualize memory using a “byte” or “word” view
- Stack stored at high addresses, stack grows “down”
- As a simplification, assume we only have 128 bytes of memory

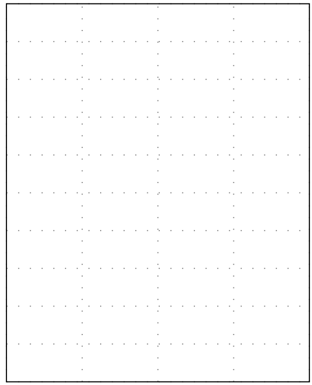
```
int  a = 3;
int* a_ptr;
a_ptr = &a;

int  b = 2;
int  c;
c = b + (*a_ptr);
```



Memory
(byte addr)

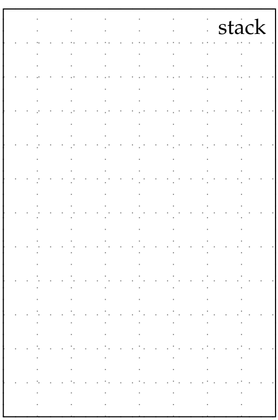


Memory
(4B word addr)

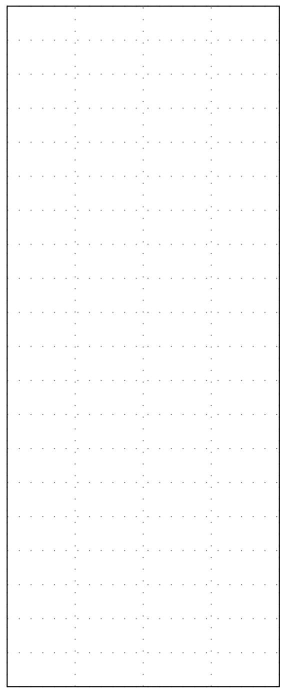


- Both code and stack are stored in 128 bytes of memory
- Stack stored at high addresses, stack grows “down”
- Code stored at low addresses, execution moves “up”
- Stack Frame: collection of data on the stack associated with function call including return value, return addr, parameters, local variables

```c
void sort( int* x_ptr, int* y_ptr )
{
  if ( (*x_ptr) > (*y_ptr) ) {
    int temp = *x_ptr;
    *x_ptr   = *y_ptr;
    *y_ptr   = temp;
  }
}

int main( void )
{
  int a = 9;
  int b = 5;
  sort( &a, &b );
  return 0;
}
```

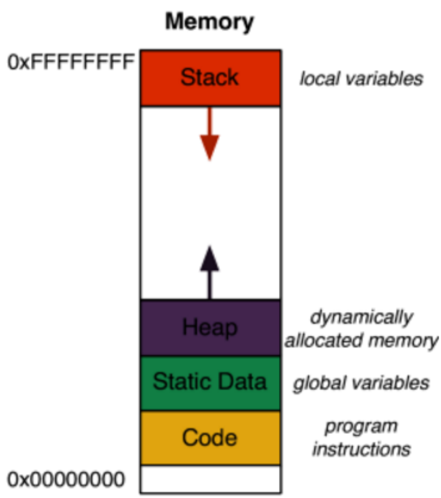


Memory
(4B word addr)



```c
#include <stdio.h>

void sort( int* x_ptr, int* y_ptr )
{
  printf( "addr of x_ptr : %p (points to %p)\n", &x_ptr, x_ptr );
  printf( "addr of y_ptr : %p (points to %p)\n", &y_ptr, y_ptr );
  if ( (*x_ptr) > (*y_ptr) ) {
    int temp = *x_ptr;
    printf( "addr of temp : %p\n", &temp  );
    *x_ptr   = *y_ptr;
    *y_ptr   = temp;
  }
}

int main( void )
{
  int a = 9;
  int b = 5;
  printf( "addr of a : %p\n", &a );
  printf( "addr of b : %p\n", &b );
  sort( &a, &b );
  return 0;
}
```

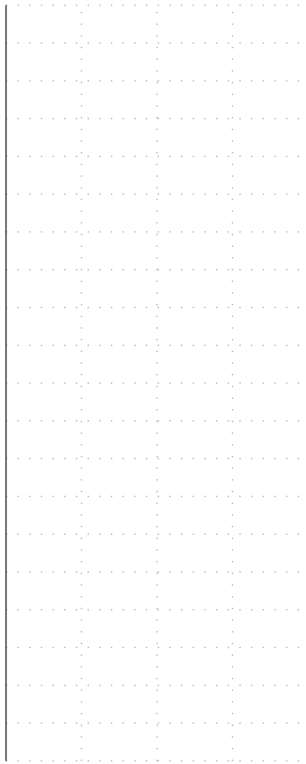
http://cpp.sh/7ymyp



- Working with the raw pointer values is challenging, especially with address space layout randomization
- Real calling conventions are more complex that the simple one used in lecture

Example stack frame for x86

Memory
(4B word addresses)



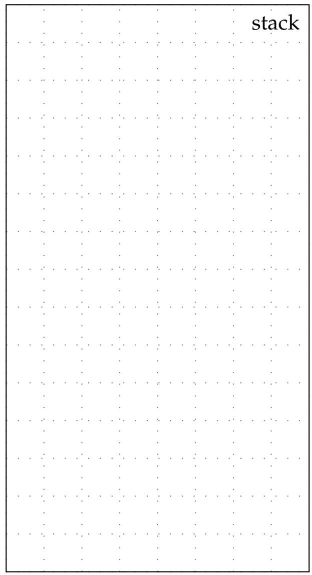
4. Pointers to Other Types

In addition to pointing to primitive types, pointers can also point to other pointers, to `structs`, or even functions.

Pointers to `struct`

- Pointer to a `struct` is declared exactly as what we have already seen
- Be careful to dereference the pointer first, then access a field

```c
typedef struct _node_t
{
  int             value;
  struct _node_t* next_ptr;
}
node_t;

int main( void )
{
  // First node
  node_t node0;
  node0.value = 3;

  node_t* node_ptr = &node0;
  (*node_ptr).value = 4;

  // Second node
  node_t node1;
  node1.value    = 5;
  node1.next_ptr = &node0;

  node_ptr = &node1;
  (*node_ptr).value                  = 6;
  (*((*node_ptr).next_ptr)).value = 7;

  return 0;
}
```



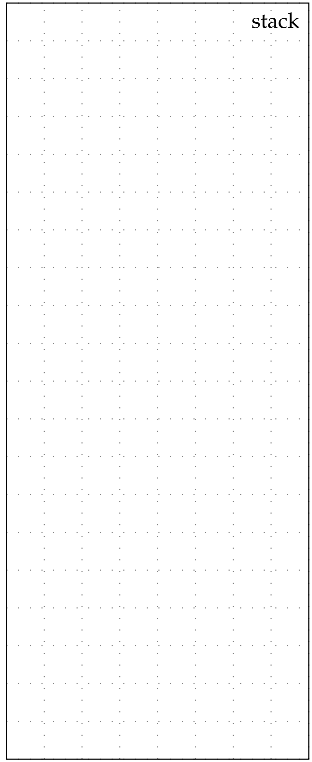
- C provides the arrow operator (`->`) as syntactic sugar
- `a->b` is equivalent to `(*a).b`

```
int main( void )
{
  ...

  node_t* node_ptr = &node0;
  node_ptr->value = 4;

  ...

  node_ptr = &node1;
  node_ptr->value           = 6;
  node_ptr->next_ptr->value = 7;
}
```

Pointers to Nothing

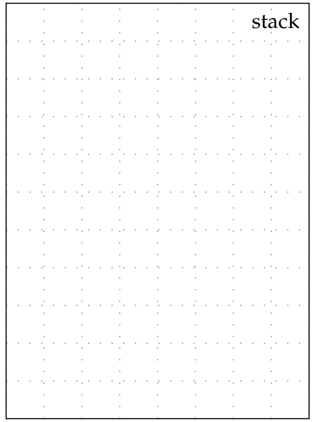
- `NULL` is defined in `stdlib.h` to be a pointer to nothing
- `NULL` can be used to indicate "there is no answer" or "error"
- Use flat-headed arrow to indicate `NULL` in stack frame diagrams
- In previous example, `NULL` can mean there is no next node

```c
#include <stddef.h>
#include <stdio.h>

typdef struct _node_t
{
  int              value;
  struct _node_t* next_ptr;
}
node_t;

int main( void )
{
  node_t node0;
  node0.value    = 3;
  node0.next_ptr = NULL;

  node_t node1;
  node1.value    = 4;
  node1.next_ptr = &node0;

  node_t node2;
  node2.value    = 5;
  node2.next_ptr = &node1;

  int sum = 0;
  node_t* node_ptr = &node2;
  while ( node_ptr != NULL ) {
    sum += node_ptr->value;
    node_ptr = node_ptr->next_ptr;
  }
  return 0;
}
```



Pointers to Pointers

```
int     a       = 3;
int*    a_ptr   = &a;
int**   a_pptr  = &a_ptr;
int*** a_ppptr = &a_pptr;

int b = ***a_ppptr + 1;
```



Pointers to Functions

- Code is also stored in memory, so a function pointer points to code
- Enables passing a *function* as a parameter to a different function
- Consider the following functions:

```
int lt( int x, int y ) { return x < y; }
int gt( int x, int y ) { return x > y; }
```

- The type of a function is the function's signature
- A function signature includes the parameter types and return type
- We don't really care about the function or parameter names
- `lt` and `gt` have the same function signature and thus the same type
- `lt` and `gt` are essentially two "values" of the same type
- We can write the type of these functions as follows:

```
int ( int, int )
```

- Recall that every type `T` has a corresponding pointer type `T*`
- So the type of a pointer to this function might look like this:

```
(int ( int, int ))*
```

- ... and declaring a variable to hold a function pointer like this:

```
(int ( int, int ))* cmp_ptr;
```

- This makes sense and would be consistent, but C actually uses a slightly different syntax for declaring a function pointer:

```
int (*cmp_ptr) ( int, int );
```

- This also makes sense since now there is a direct connection between a function declaration and a function pointer:

```
int lt         ( int x, int y );
int (*cmp_ptr) ( int,   int   );
```

- The type of a function pointer is complex, so use a `typedef`

```
typedef int (*cmp_ptr_t) ( int, int );
cmp_ptr_t cmp_ptr;
```

- The address-of operator (`&`) applied to a function name evaluates to a pointer to that function

```
typedef int (*cmp_ptr_t) ( int, int );
cmp_ptr_t cmp_ptr = &gt;
```

- We can dereference a function pointer and use the call operator (`()`) to call a function via function pointer

```
typedef int (*cmp_ptr_t) ( int, int );
cmp_ptr_t cmp_ptr = &gt;
int result = (*cmp_ptr)( 3, 4 );
```

```c
#include <stdio.h>

int lt( int x, int y ) { return x < y; }
int gt( int x, int y ) { return x > y; }

typedef int (*cmp_ptr_t) ( int, int );

void sort( int* x_ptr, int* y_ptr, cmp_ptr_t cmp_ptr )
{
  // Dereference function pointer, then call function
  if ( (*cmp_ptr)( (*x_ptr), (*y_ptr) ) ) {
    int temp = *x_ptr;
    *x_ptr   = *y_ptr;
    *y_ptr   = temp;
  }
}

void sort3( int* x_ptr, int* y_ptr, int* z_ptr,
            cmp_ptr_t cmp_ptr )
{
  sort( x_ptr, y_ptr, cmp_ptr );
  sort( y_ptr, z_ptr, cmp_ptr );
  sort( x_ptr, y_ptr, cmp_ptr );
}

int main( void )
{
  int a = 9; int b = 5; int c = 3;

  sort3( &a, &b, &c, &gt );
  printf(" %d < %d < %d \n", a, b, c );

  sort3( &a, &b, &c, &lt );
  printf(" %d > %d > %d \n", a, b, c );

  return 0;
}
```

http://cpp.sh/36nqu