ECE 2400 Computer Systems Programming
Fall 2021

Topic 6: C Dynamic Allocation

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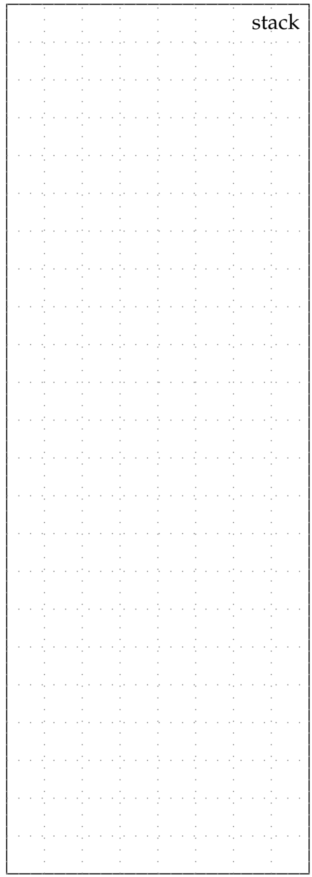
1. Using `malloc` to Allocate Memory

- Let's revisit an example we saw in a previous topic
- Assume we wish to refactor appending a node to a chain into its own function

Draw a state diagram corresponding to the execution of this program

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

node_t* append( node_t* n_ptr,
                int value )
{
  node_t node;
  node.value    = value;
  node.next_ptr = n_ptr;
  return &node;
}

int main( void )
{
  node_t* n_ptr = NULL;
  n_ptr = append( n_ptr, 3 );
  n_ptr = append( n_ptr, 4 );
  return 0;
}
```



- Let's consider a similar idea for arrays
- Assume we wish to refactor allocating an array and then initializing all elements to zero into its own function

```c
#include <stddef.h>

int* init_array( int n )
{
  int x[n];

  for ( int i=0; i<n; i++ )
    x[i] = 0;

  return x;
}

int main( void )
{
  int* a = init_array(3);
  return 0;
}
```

List two errors with this function:

1. ______________________________

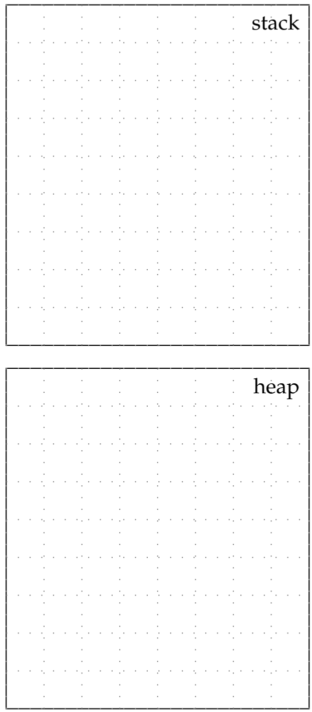
   ____

2. ______________________________

   ____

- Dynamic memory allocation uses the heap (new region of memory)
- Because dynamically allocated variables are not on a function's stack frame, they are not deallocated when a function returns
- We can dynamically allocate variables on the heap using malloc
- malloc takes the number of bytes to allocate as a parameter and returns a pointer to the new variable allocated on the heap
- Since the amount of memory allocated is dynamic, we can create arrays where the number of elements is not known until runtime
- malloc is defined in stdlib.h

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

*a_ptr = 42;

int* b_ptr =
  malloc( 4 * sizeof(int) );

b_ptr[0] = 10;
b_ptr[1] = 11;
b_ptr[2] = 12;
b_ptr[3] = 13;
```



Draw a state diagram corresponding to the execution of this program

```
typedef struct
{
  double real;
  double imag;
}
complex_t;

int main( void )
{
  complex_t* c_ptr0 =
    malloc( sizeof(complex_t) );

  c_ptr0->real = 1.5;
  c_ptr0->imag = 3.5;

  complex_t* c_ptr1 =
    malloc( sizeof(complex_t) );

  c_ptr1->real = c_ptr0->real;
  c_ptr1->imag = c_ptr0->imag;

  return 0;
}
```

stack

heap

- Assume we wish to refactor appending a node to a chain into its own function

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

node_t* append( node_t* n_ptr,
                int value )
{
  node_t* new_ptr =
    malloc( sizeof(node_t) );

  new_ptr->value    = value;
  new_ptr->next_ptr = n_ptr;
  return new_ptr;
}

int main( void )
{
  node_t* n_ptr = NULL;
  n_ptr = append( n_ptr, 3 );
  n_ptr = append( n_ptr, 4 );
  return 0;
}
```

stack

heap

- Assume we wish to refactor allocating an array and then initializing all elements to zero into its own function

```c
#include <stddef.h>

int* init_array( int n )
{
  int* x = malloc( n * sizeof(int) );

  for ( int i=0; i<n; i++ )
    x[i] = 0;

  return x;
}

int main( void )
{
  int* a = init_array(3);
  return 0;
}
```

How does this address the two errors we identified earlier?

1. ______________________________

   ____

2. ______________________________

   ____

2. Using `free` to Deallocate Memory

Draw a state diagram corresponding to the execution of this program

```
typedef struct
{
  double real;
  double imag;
}
complex_t;

int main( void )
{
  complex_t* c_ptr =
    malloc( sizeof(complex_t) );

  c_ptr->real = 1.5;
  c_ptr->imag = 3.5;

  c_ptr =
    malloc( sizeof(complex_t) );

  c_ptr->real = 2.5;
  c_ptr->imag = 4.5;

  return 0;
}
```

stack

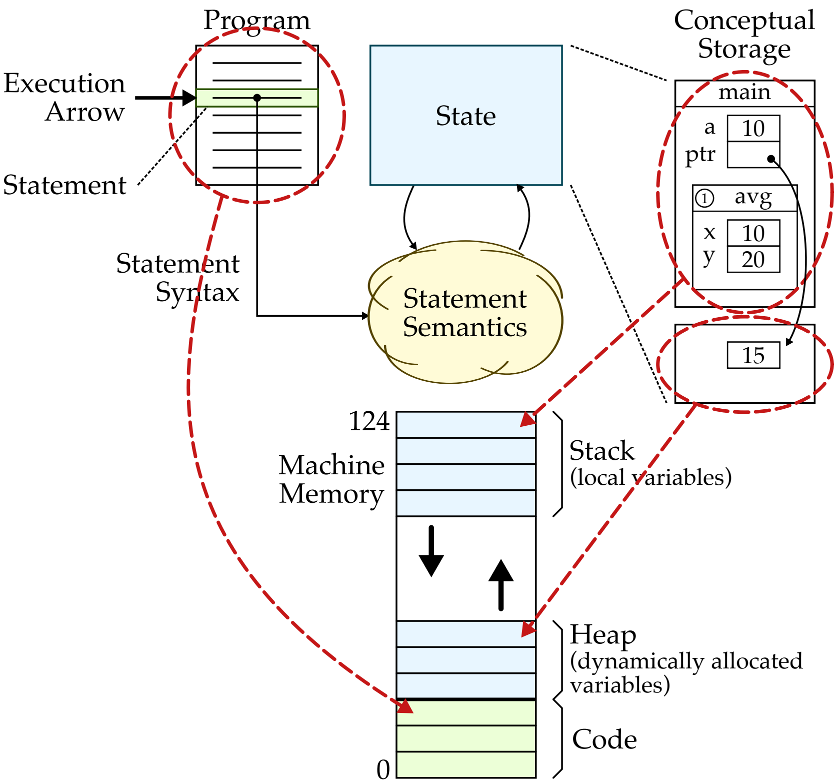
heap

- Every call to `malloc` must have corresponding call to `free`
- `free` takes a pointer to a dynamically allocated variable

```c
typedef struct
{
  double real;
  double imag;
}
complex_t;

int main( void )
{
  complex_t* c_ptr =
    malloc( sizeof(complex_t) );

  c_ptr->real = 1.5;
  c_ptr->imag = 3.5;

  free( c_ptr );

  c_ptr =
    malloc( sizeof(complex_t) );

  c_ptr->real = 2.5;
  c_ptr->imag = 4.5;

  free( c_ptr );

  return 0;
}
```

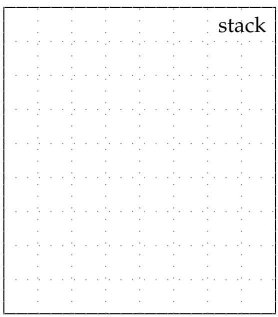
3. Mapping Conceptual Storage to Machine Memory

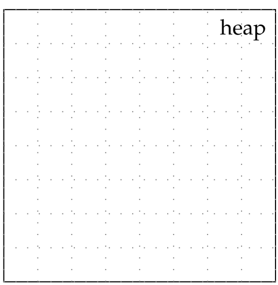
- Recall that our current use of state diagrams is conceptual
- Real machine uses memory to store variables
- Real machine does not use "arrows", uses memory addresses
- Heap is stored above code and grows *up*

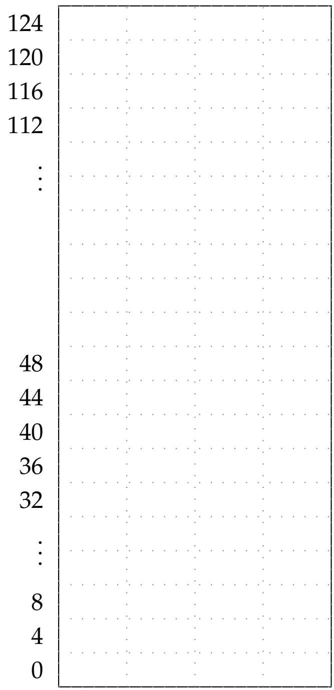


```c
int  a = 3;
int* a_ptr = &a;

int* b_ptr =
  malloc( sizeof(int) );
*b_ptr = 42;

int* c =
  malloc( 4 * sizeof(int) );
c[0] = 10;
c[1] = 11;
c[2] = 12;
c[3] = 13;
```

Memory
(4B word addr)







Machine memory in real systems

- Machine memory size ranges from KBs (embedded) to TBs (server)
- Lowest address range reserved to detect NULL pointer dereference
- Static data region is used for global variables
- Machine memory as shown is really the *virtual memory space*
- Different programs have their own virtual memory spaces mapped to a single large *physical memory space*