Recursion

Part 3

1

Program Structure

How they work

2

Program Structure

- When writing a program, you must be aware how it works "behinds the scenes"
- In particular, you must understand memory and how it is used.

3

Program Structure

- There are possible issues that can arise that can negatively impact your programs
- … and possibly make them unresponsive

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Some Terminology

- When you call a function, you can specify pieces of data called *arguments*
- These match the format of the function – which is specified in its *parameters*
- Basically
  - arguments are *passed* to the parameters
  - they match, in order, on a one-to-one basis
  - arguments ➔ parameters

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Scope

- *Scope* refers how a variable/function is bound (i.e. visible to the rest of your program)
- Data is often stored differently, based on its scope

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Global Variables

- You can declare variables outside functions
- This are visible to all functions in the class (or module)
- These are known as *global variables*

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Global Variables

- They can be useful for sharing data between functions
- However, it can be problematic
  - variables can be modified in ways that cause side effects in your program
  - it is better to use local variables and pass them to other functions

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Global Variables

```
int total;

void printTotal()
{
   System.out.println(total);
}

int main()
{
   total = 1000;
   ...
```

Visible to all functions!

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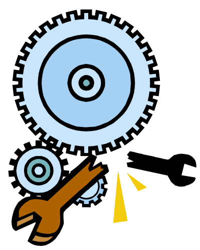
Global Variable Problems



- They can be useful for sharing data between functions
- However, it can be problematic
  - variables can be modified in ways that cause side effects in your program
  - it is better to use local variables and pass them to other functions

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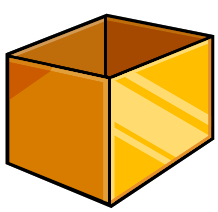
Local Variables

- When you create functions, each can have *local* variables
- These are only "visible" to the function in which they are declared
- So, other functions cannot access them



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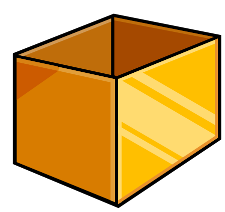
Variable Scope

- Different functions can have local variables with the same name
- Why?
  - they can't "see" each other
  - they are different variables, anyway
  - … so, there is no problem



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Variable Scopes

```
int hello()
{
   int x;
}

int main()
{
   int x;
}
```

Not the same variable

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Variable Scopes

```
int hello()
{
   double x;
}

int main()
{
   int x;
}
```

Don't have to be the same type
(they are different variables)

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Example: Average Function

```
double average(double a, double b)
{
   double avg;

   avg = (a + b) / 2;
   return avg;
}
```

Parameters are also local variables

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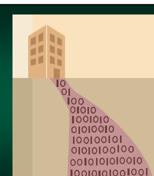

The System Stack & Heap

Making the Functions Function & Data Delightful

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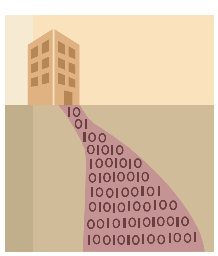
The System Stack & Heap

- Computers maintain two types of memory for running programs: *The Stack* and *The Heap*
- Each has a specific purpose, and, in tandem, they make modern programs possible



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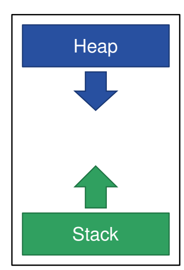
The System Stack & Heap

- Each is stored in your computer's main memory
- They grow "towards" each other (and, hopefully, will never meet)



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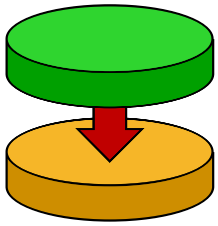
The System Stack

- The System Stack is used to store local variables and allow your program to support functions
- So, anytime you call a function or declare a local variable, a stack is used



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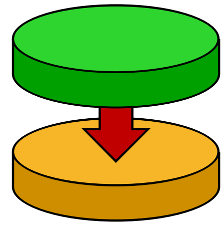
The System Stack

- Each time a function calls another function an *Activation Record* is placed on the *stack*
- It contains all the information that the instance of a function requires



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Contents of the Activation Record

- The Activation Record contains:
  - parameters
  - local variables
  - return address (used by the processor)
- Data in an activation record is temporary to that "instance" of a function
- In other words, data does not persist after the function ends

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The Power of Stacks

- Because the stack is a First-In-Last-Out structure, it allows function nesting
- And even a more powerful concept – *recursion*
- Examples
  - web browser "back button"
  - undo sequence in a text editor

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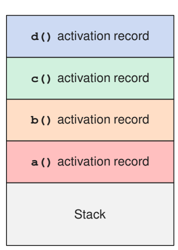
Nesting Activation Records

- For example:
  - `main()` calls `a()`
  - `a()` calls `b()`
  - `b()` calls `c()`
  - `c()` calls `d()`
- Each activation record is pushed onto the stack



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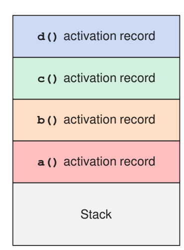
Nesting Activation Records

- When a function "returns", its activation record is pop'd and discarded
- The local variables cease to exist
- Only the return value is passed to the caller



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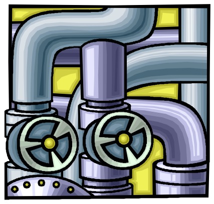
The Heap

- Nothing on the system stack persists forever – it is quite temporary
- So, how do we make data last indefinitely? …or, as long as our program is active



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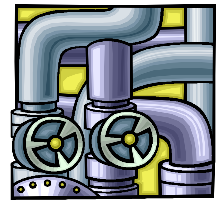
The Heap

- *The Heap* is used to store *dynamic* allocation
- It is allocated *as needed*
- … not to be confused with the Heap Data Structure (which we will cover later)



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The Heap

- Anytime you create objects using *"new"*…
  - the heap is used to allocate storage
  - system performs garbage collection after the memory is no longer needed
- Unlike the stack, data persists regardless of function calls

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Reference Types

The objective of Object Oriented Programs

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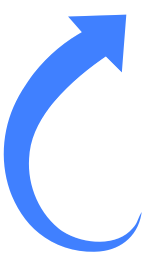
Reference Types



- Most languages are based on largely based on building abstract data types called *reference types*
- They are links to nebulous *objects* – whose contents & implementation are unknown

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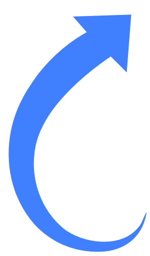
Reference Types



- This is known as *object-oriented programming*
- … and is the basis of all modern programming languages

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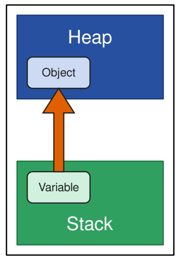
Reference Types

- So, local variables exist on the stack
- But... they reference objects stored on the system heap



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Garbage Collection

- Programming languages use *garbage collection* reclaim unused data from the heap
- Policy is to reclaim the memory used by objects that *can no longer be accessed (i.e. **no** references)*

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Garbage Collection

- So, languages maintain a counter on each object
  - if you add a reference, it increments
  - if a reference is removed, it decrements
- When it reaches zero, the object can be removed

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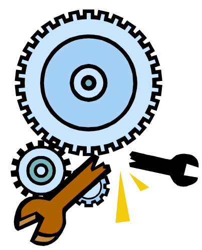
Loitering

- It is possible to "remove" an item from the ADT, but accidently keep a reference (link) to it
- The item is effectively an *orphan* - it will be never be accessed again by the ADT



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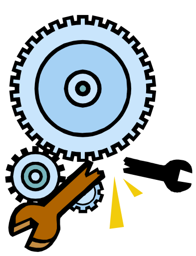
Loitering

- The garbage collector has no way to know unless it's overwritten
- So, under this condition, the object is said to *loiter* – stay in memory with no purpose
- This can negatively affect performance



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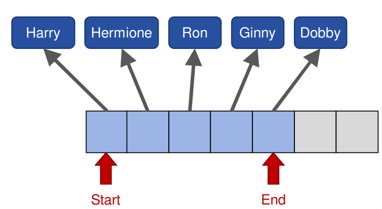
Array Storing a List (partially filled)



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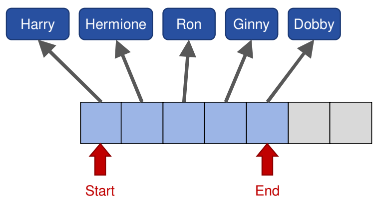
Delete Last – Move End



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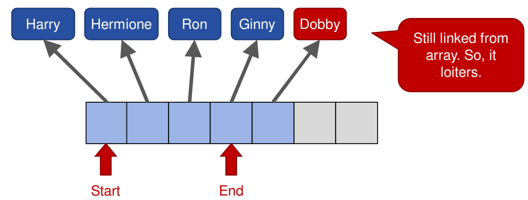
Dobby is still linked…



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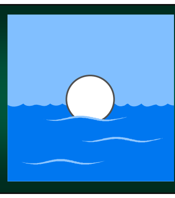

Pools

Okay, now it's getting weird

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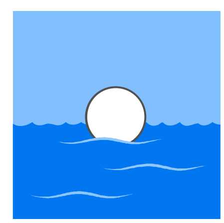
Pools

- Creating and destroying objects is expensive on the heap
- So, we want to minimize the constant creation and deletion of new nodes



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Why?

- Arrays can be wasteful …
  - in space – when there are partially
  - in time – created and destroyed frequently
- Linked lists can be wasteful…
  - require memory to be allocated each time a node is created
  - puts a lot of work on the heap

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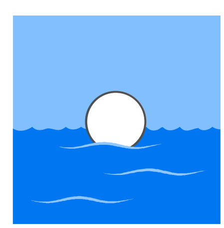
Jump in the Pool

- One solution is to maintain a *pool*
- This is a collection of nodes that are allocated early and are used as, kind of, a recycling bin



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Jump in the Pool

- If a node is needed, one is removed from the pool
- If a node is removed, and the array has room, it is placed back in the array (after the data field is set to null, of course)

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Even more approaches

- You can also use a "pool" for linked lists
- So, your Linked List class
  - would have a linked list of valid nodes
  - and another list of unused notes
  - the danger here is that you don't limit the size of the pool – and it grows ***forever***
  - so, if you use two linked lists, keep a pool member count

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Recursion

The best way to learn recursion…
is to, first, learn recursion!

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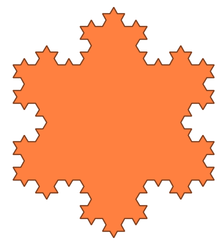
Recursion

- *Recursion* occurs when a function directly or indirectly calls *itself*
- This results in a loop
- However, it doesn't use iterative structures such as For or While loops



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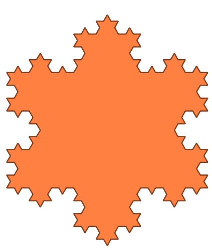
Recursion

- This can greatly simply programming tasks
- Commonly used to traverse a graph, tree, or run complex calculations
- While powerful, it is costly on computer resources
- …and can also create pitfalls



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Breaking a Problem Down

- Recursion allows a problem to be broken down into smaller instances of themselves
- Each call will represent a smaller, simpler, version of the same problem
- Eventually, it will reach a *"base case"* which will not require any more recursive calls

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Where Recursion Shines

- When the program can be broken into smaller pieces, recursion is a great solution
- Examples:
  - graph traversal – searching, etc.…
  - state machines
  - sorting
  - many math problems

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Danger: Never Ending

- If you break down a task into smaller parts… at some point, it should become a single value
- If not, the function will never end and will recurse forever – *at least until the computer runs out of resources*

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Danger: Accidental Recursion

- Accidental recursion is a common mistake by beginner programmers
- Recursion can be done directly or indirectly
  - for example: A calls B, B calls C, C calls A
  - organize your code carefully!

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Results of These Dangers…

- Runaway recursion
  - function will recurse ***forever***
  - eventually all memory is exhausted
- You will see either…
  - "stack overflow" error
  - "heap exhaustion" error

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To infinity… but not beyond

```
void toInfinity()
{
   System.out.println("To infinity!");
   toInfinity();
   System.out.println("and beyond!");
}
```

We never get here!

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Designing a Recursive Function

- Does the problem lend itself to recursion?
  - can the problem be broken down into smaller instances of itself?
  - is there a iterative version that is better
- Is there a base case?
  - is there a case where recursion will stop?
  - remember: ALWAYS have a stopping point!

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Example: Factorials

- Factorials are classic mathematical problem that lends itself easily to recursion
- If you don't remember, a factorial of *n* is defined as the value of n multiplied by all lesser integers ≥ 1
- For example: 5! → 5×4×3×2×1 → 120

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Example: Factorials

- It should be easy to observe that *n!* can be defined as *n × (n – 1)!*
- So, n! can be computed by multiplying n by the factorial of one less than it
- 4! → 4 × 3! → 4 × 3 × 2! → 4 × 3 × 2 × 1

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Example: Factorials

```
int factorial(int n)
{
   if (n == 1)
   {
     return 1;
   }
   else
   {
     return n * factorial(n - 1);
   }
}
```

Base case

Recursion

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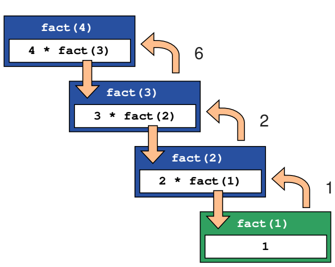
Example Factorial



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Iteration vs. Recursion

- Any program that can be expressed using recursion, can be done through iteration
- The recursive solution will often be far simpler – more "eloquent" to read
- … but is never more efficient due to the overhead of calling functions

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Historical Perspective

Some really cool solutions!

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Some Well-known Problems

- Sorting
- Searching
- Shortest paths in a graph
- Minimum spanning tree
- Primality testing

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Some Well-known Problems

- Traveling salesman problem
- Knapsack problem
- Chess
- Towers of Hanoi
- Program termination

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Fibonacci Numbers

- Rabbits tend to reproduce like… well… rabbits
- Mathematician *Fibonacci* analyzed this situation and created a mathematical system to predict this phenomena
- It is used today in finance, simulation, and several computer science algorithms

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Fibonacci Numbers

- The problem:
  - start with a pair of rabbits
  - at month #2, the rabbits begin to reproduce
  - the female gives birth to a new pair of rabbits: one male and one female
  - babies mature at the same rate and will have more babies
- Fibonacci number sequences predict the total pairs after *n* months

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Fibonacci Numbers

- After two months, the female gives birth creating a new pair…. then they get pregnant again!
- This continues forever…..
- Sequence: 1, 1, 2, 3, 5, 8, 13, 21, 34, ...

```
if n == 1 then Fib(n) = 1
if n == 2 then Fib(n) = 1
if n > 2  then Fib(n) = Fib(n-2) + Fib(n-1)
```


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Example 2: Fibonacci Numbers

```
f(3) = f(2) + f(1) = 1 + 1 = 2

f(4) = f(3) + f(2) = 2 + 1 = 3

f(5) = f(4) + f(3) = 3 + 2 = 5

f(6) = f(5) + f(4) = 5 + 3 = 8
```


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Example: Fibonacci Numbers

```
int fib(int n)
{
  if (n == 1 || n == 2)
  {
    return 1;
  }
  else
  {
    return fib(n-2) + fib(n-1);
  }
}
```

Recursion

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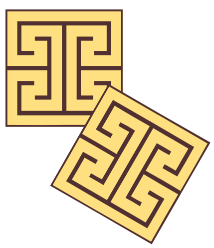
Greatest Common Denominator

- A common problem in computer science is finding the greatest (or least) common denominator for two integers
- For example:
  the GCD of 64 and 40 is 8



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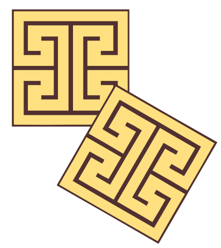
Greatest Common Denominator

- *Euclid* created an ingenious algorithm for finding the greatest common divisor
- This is known example of recursion – first solved using geometry using the metaphor of a tile floor



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Euclid's Algorithm

- Euclid's algorithm is recursive
- You reapply the expression below until the second value of gcd(n, m) is zero.
- In this case, n will be the CGD

```
gcd(n, m) → gcd(m, n mod m)
```


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Euclid's Algorithm Examples

- 60 and 24
  - gcd(60, 24) → gcd(24,12) → gcd(12, 0)
  - the result is 12
- 84 and 20
  - gcd(84, 20) → gcd(20, 4) → gcd(4, 0)
  - result is 4
- These might seem trivial, but it can find HUGE numbers quite easily

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