Model of Execution

Lecture Question

Question: In a package named "oop" create a Scala **class** named "Team" and a Scala **object** named "Referee".

Team will have:

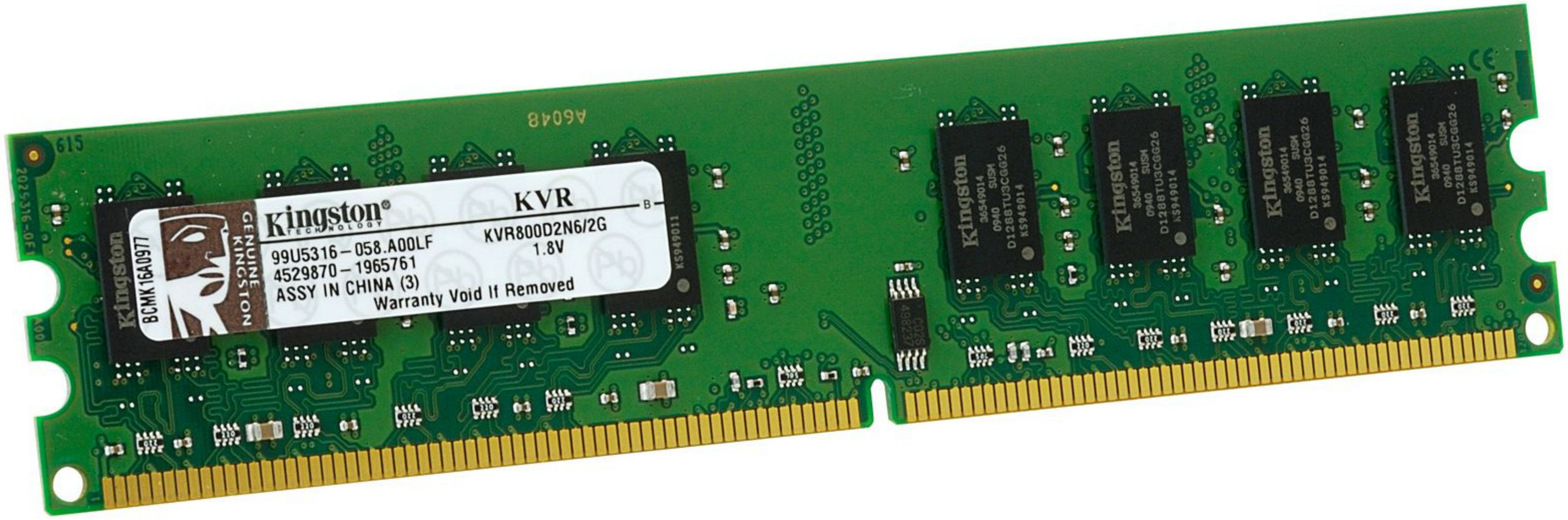
- State values of type Int representing the strength of the team's offense and defense with a constructor to set these values. The parameters for the constructor should be offense then defense
- A third state variable named "score" of type Int that is not in the constructor, is declared as a **var**, and is initialized to 0

Referee will have:

- A method named "playGame" that takes two Team objects as parameters and return type Unit. This method will alter the state of each input Team by setting their scores equal to their offense minus the other Team's defense. If a Team's offense is less than the other Team's defense their score should be 0 (no negative scores)
- A method named "declareWinner" that takes two Teams as parameters and returns the Team with the higher score. If both Teams have the same score, return a new Team object with offense and defense both set to 0

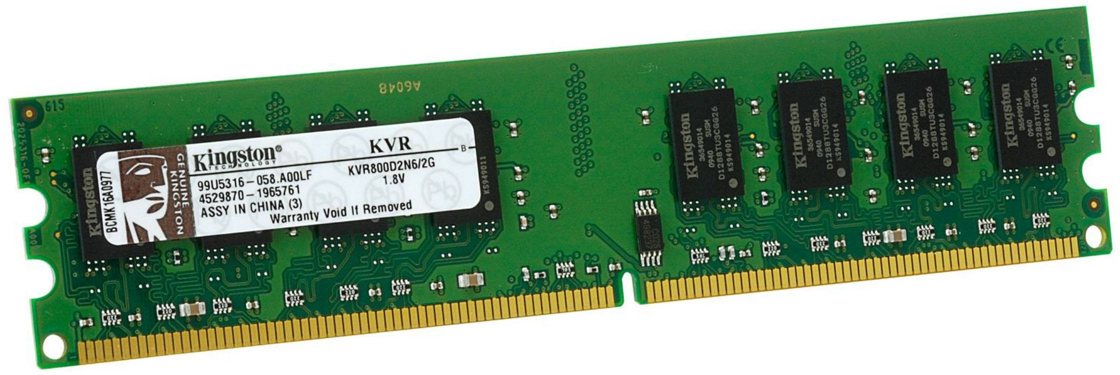
Let's Talk About Memory

- Random Access Memory (RAM)
  - Access any value by index
  - Effectively a giant array
- All values in your program is stored here



Let's Talk About Memory

- Significantly faster than reading/writing to disk
  - Even with an SSD
- Significantly more expensive than disk space



>

Let's Talk About Memory

- Operating System (OS) controls memory
- On program start, OS allocates a section of memory for our program
    - Gives access to a range of memory addresses/indices

Index	Value
...	...
27173	<Used by another program>
27172	<Our Program Memory>
27171	<Our Program Memory>
27170	<Our Program Memory>
27169	<Our Program Memory>
27168	<Our Program Memory>
27167	<Our Program Memory>
27166	<Our Program Memory>
27165	<Our Program Memory>
27164	<Our Program Memory>
27163	<Our Program Memory>
27162	<Our Program Memory>
27161	<Used by another program>
...	...

Program Memory

- Some space is reserved for program data
- Details not important to CSE116
- The rest will be used for our data
- Data stored in the **memory stack**

Index	Value
...	...
27173	<Used by another program>
27172	<Command line args>
27171	<Our Program Memory>
27170	<Our Program Memory>
27169	<Our Program Memory>
27168	<Our Program Memory>
27167	<Our Program Memory>
27166	<Our Program Memory>
27165	<Our Program Memory>
27164	<Program Data>
27163	<Program Data>
27162	<Program Data>
27161	<Used by another program>
...	...

Memory Stack Example

```
function computeFactorial(n){
  result = 1
  for (i=1; i<=n; i++) {
    result *= i
  }
  return result
}

function main(commandLineArgs){
  i = 5
  n = computeFactorial(i)
  print(n)
}
```

Note: This example is language independent and will focus on the concept of memory. Each language will have differences in how memory is managed

Memory Stack Example

```
function computeFactorial(n){
  result = 1
  for (i=1; i<=n; i++) {
    result *= i
  }
  return result
}

function main(commandLineArgs){
  i = 5
  n = computeFactorial(i)
  print(n)
}
```

- Command line arguments added to the stack

Index	Value
...	...
27173	<Used by another program>
27172	commandLineArgs
27171	
27170	
27169	
27168	
27167	
27166	
27165	
27164	
27163	
27162	
27161	<Used by another program>
...	...

Memory Stack Example

```
function computeFactorial(n){
  result = 1
  for (i=1; i<=n; i++) {
    result *= i
  }
  return result
}

function main(commandLineArgs){
➔ i = 5
  n = computeFactorial(i)
  print(n)
}
```

- A variable named i of type Int is added to the stack
- The variable i is assigned a value of 5

Index	Value
...	...
27173	<Used by another program>
27172	commandLineArgs
27171	name:i, value:5 (main)
27170	
27169	
27168	
27167	
27166	
27165	
27164	
27163	
27162	
27161	<Used by another program>
...	...

Memory Stack Example

```
function computeFactorial(n){
  result = 1
  for (i=1; i<=n; i++) {
    result *= i
  }
  return result
}

function main(commandLineArgs){
  i = 5
➜ n = computeFactorial(i)
  print(n)
}
```

- The program enters a call to computeFactorial
- A new **stack frame** is created for this call

Index	Value
...	...
27173	<Used by another program>
27172	commandLineArgs
27171	name:i, value:5 (main)
27170	<computeFactorial stack frame>
27169	
27168	
27167	
27166	
27165	
27164	
27163	
27162	
27161	<Used by another program>
...	...

Memory Stack Example

```
function computeFactorial(n){
  result = 1
  for (i=1; i<=n; i++) {
    result *= i
  }
  return result
}

function main(commandLineArgs){
  i = 5
  n = computeFactorial(i)
  print(n)
}
```

- Add n to the stack and assign it the value from the input argument

Index	Value
...	...
27173	<Used by another program>
27172	commandLineArgs
27171	name:i, value:5 (main)
27170	<computeFactorial stack frame>
27169	name:n, value:5 (computeFactorial)
27168	
27167	
27166	
27165	
27164	
27163	
27162	
27161	<Used by another program>
...	...

Memory Stack Example

```
function computeFactorial(n){
  result = 1
  for (i=1; i<=n; i++) {
    result *= i
  }
  return result
}

function main(commandLineArgs){
  i = 5
  n = computeFactorial(i)
  print(n)
}
```

- Add result to the stack and assign it the value 1

Index	Value
...	...
27173	<Used by another program>
27172	commandLineArgs
27171	name:i, value:5 (main)
27170	<function call stack frame>
27169	name:n, value:5 (function)
27168	name:result, value:1 (function)
27167	
27166	
27165	
27164	
27163	
27162	
27161	<Used by another program>
...	...

Memory Stack Example

```
function computeFactorial(n){
  result = 1
  for (i=1; i<=n; i++) {
    result *= i
  }
  return result
}

function main(commandLineArgs){
  i = 5
  n = computeFactorial(i)
  print(n)
}
```

- Begin loop block
- Add i to the stack and assign it the value 1
  - This is different from the i declared in main since they are in different frames

Index	Value
...	...
27173	<Used by another program>
27172	commandLineArgs
27171	name:i, value:5 (main)
27170	<function call stack frame>
27169	name:n, value:5 (function)
27168	name:result, value:1 (function)
27167	<loop block>
27166	name:i, value:1 (function)
27165	
27164	
27163	
27162	
27161	<Used by another program>
...	...

Memory Stack Example

```
function computeFactorial(n){
  result = 1
  for (i=1; i<=n; i++) {
    result *= i
  }
  return result
}

function main(commandLineArgs){
  i = 5
  n = computeFactorial(i)
  print(n)
}
```

- Iterate through the loop
- look for variable named result in current stack frame
  - Found it outside the loop block
  - Update it's value (remains 1 on first iteration)

Index	Value
...	...
27173	<Used by another program>
27172	commandLineArgs
27171	name:i, value:5 (main)
27170	<function call stack frame>
27169	name:n, value:5 (function)
27168	name:result, value:1 (function)
27167	<loop block>
27166	name:i, value:1 (function)
27165	
27164	
27163	
27162	
27161	<Used by another program>
...	...

Memory Stack Example

```
function computeFactorial(n){
  result = 1
  for (i=1; i<=n; i++) {
    result *= i
  }
  return result
}

function main(commandLineArgs){
  i = 5
  n = computeFactorial(i)
  print(n)
}
```

- Iterate through the loop
- look for variable named i in current stack frame
  - Found it inside the loop block
  - *Some languages look outside the current frame

Index	Value
...	...
27173	<Used by another program>
27172	commandLineArgs
27171	name:i, value:5 (main)
27170	<function call stack frame>
27169	name:n, value:5 (function)
27168	name:result, value:1 (function)
27167	<loop block>
27166	name:i, value:2 (function)
27165	
27164	
27163	
27162	
27161	<Used by another program>
...	...

Memory Stack Example

```
function computeFactorial(n){
  result = 1
  for (i=1; i<=n; i++) {
    result *= i
→ }
  return result
}

function main(commandLineArgs){
  i = 5
  n = computeFactorial(i)
  print(n)
}
```

- Iterate through the loop until conditional is false

Index	Value
...	...
27173	<Used by another program>
27172	commandLineArgs
27171	name:i, value:5 (main)
27170	<function call stack frame>
27169	name:n, value:5 (function)
27168	name:result, value:120 (function)
27167	<loop block>
27166	name:i, value:5 (function)
27165	
27164	
27163	
27162	
27161	<Used by another program>
...	...

Memory Stack Example

```
function computeFactorial(n){
  result = 1
  for (i=1; i<=n; i++) {
    result *= i
  }
→ return result
}

function main(commandLineArgs){
  i = 5
  n = computeFactorial(i)
  print(n)
}
```

- End of a code block is reached
- Delete ALL stack storage used by that block!
  - The variable i fell out of scope and no longer exists

Index	Value
...	...
27173	<Used by another program>
27172	commandLineArgs
27171	name:i, value:5 (main)
27170	<function call stack frame>
27169	name:n, value:5 (function)
27168	name:result, value:120 (function)
27167	
27166	
27165	
27164	
27163	
27162	
27161	<Used by another program>
...	...

Memory Stack Example

```
  function computeFactorial(n){
    result = 1
    for (i=1; i<=n; i++) {
      result *= i
    }
➔   return result
  }

  function main(commandLineArgs){
    i = 5
    n = computeFactorial(i)
    print(n)
  }
```

- End of a function is reached
- Delete ALL stack storage used by that stack frame!
- Replace function call with its return value

Index	Value
...	...
27173	<Used by another program>
27172	commandLineArgs
27171	name:i, value:5 (main)
27170	function returned: 120
27169	
27168	
27167	
27166	
27165	
27164	
27163	
27162	
27161	<Used by another program>
...	...

Memory Stack Example

```
function computeFactorial(n){
  result = 1
  for (i=1; i<=n; i++) {
    result *= i
  }
  return result
}

function main(commandLineArgs){
  i = 5
➔ n = computeFactorial(i)
  print(n)
}
```

- Declare n
- Assign return value to n

Index	Value
...	...
27173	<Used by another program>
27172	commandLineArgs
27171	name:i, value:5 (main)
27170	name:n, value:120 (main)
27169	
27168	
27167	
27166	
27165	
27164	
27163	
27162	
27161	<Used by another program>
...	...

Memory Stack Example

```
function computeFactorial(n){
  result = 1
  for (i=1; i<=n; i++) {
    result *= i
  }
  return result
}

function main(commandLineArgs){
  i = 5
  n = computeFactorial(i)
➔ print(n)
}
```

- Print n to the screen
- At this point:
  - No memory of variables n (function), i (function), or result

Index	Value
...	...
27173	<Used by another program>
27172	commandLineArgs
27171	name:i, value:5 (main)
27170	name:n, value:120 (main)
27169	
27168	
27167	
27166	
27165	
27164	
27163	
27162	
27161	<Used by another program>
...	...

Memory Stack Example

```
function computeFactorial(n){
  result = 1
  for (i=1; i<=n; i++) {
    result *= i
  }
  return result
}

function main(commandLineArgs){
  i = 5
  n = computeFactorial(i)
  print(n)
}
```

- End of program
- Free memory back to the OS

Index	Value
...	...
27173	<Used by another program>
27172	
27171	
27170	
27169	
27168	
27167	
27166	
27165	
27164	
27163	
27162	
27161	<Used by another program>
...	...

Memory Stack Example

```
function computeFactorial(n){
  result = 1
  for (i=1; i<=n; i++) {
    result *= i
  }
  return result
}

function main(commandLineArgs){
  i = 5
  n = computeFactorial(i)
  print(n)
}
```

- No memory of our program

Index	Value
...	...
27173	<Used by another program>
27172	
27171	
27170	
27169	
27168	
27167	
27166	
27165	
27164	
27163	
27162	
27161	<Used by another program>
...	...

Memory Heap

What if our data needs to change size?

Memory Heap

Index	Value
...	...
27173	<Used by another program>
27172	commandLineArgs
27171	name:i, value:5 (main)
27170	name:data, value:List of Ints (main)
27169	name:n, value:120 (main)
27168	
27167	
27166	
27165	
27164	
27163	
27162	
27161	<Used by another program>
...	...

```
...
data.addValue(78)
...
```

- Variable data has values before and after it in memory
- Where do we store 78?
    - On the heap

Memory Heap

Index	Value
...	...
27173	<Used by another program>
27172	commandLineArgs
27171	name:i, value:5 (main)
27170	name:data, value:97197 (main)
27169	name:n, value:120 (main)
27168	
27167	
27166	
27165	
27164	
27163	
27162	
27161	<Used by another program>
...	...

Index	Value
...	...
97197	List of Ints
97198	List of Ints
97199	
...	...

- Heap memory is dynamic
- Can be anywhere in RAM
  - Location not important
  - Location can change
- Use references to find data
  - Variable data only stores a reference to the List of Ints

Memory Heap

Index	Value
...	...
27173	<Used by another program>
27172	commandLineArgs
27171	name:i, value:5 (main)
27170	name:data, value:97197 (main)
27169	name:n, value:120 (main)
27168	
27167	
27166	
27165	
27164	
27163	
27162	
27161	<Used by another program>
...	...

Index	Value
...	...
97197	List of Ints
97198	List of Ints
97199	
...	...

- Objects *usually* stored in heap memory
- [In Scala] Int, Double, Boolean, Char, and few others are all stored on the stack
  - All other types are stored in the heap, including every type you define

Memory Heap Example

Index	Value
...	...
63051	<Used by another program>
63052	commandLineArgs
63053	name:data, value:38772 (main)
63054	
63055	
63056	
63057	<Used by another program>
...	...

Index	Value
...	...
38772	ClassWithStateObject
38773	-stateVar value:0
38774	
...	...

```
class ClassWithState{
  int stateVar = 0;
}
```

```
function addToState(input){
  input.stateVar += 1
}

function main{
  data = new ClassWithState
  addToState(data)
  println(data.stateVar)
}
```

- Create instance of ClassWithState on the heap
- Store **memory address** of the new object in data

Memory Heap Example

Index	Value
...	...
63051	<Used by another program>
63052	commandLineArgs
63053	name:data, value:38772 (main)
63054	<function call stack frame>
63055	name:input, value:38772 (function)
63056	
63057	<Used by another program>
...	...

Index	Value
...	...
38772	ClassWithStateObject
38773	-stateVar value:0
38774	
...	...

```
class ClassWithState{
  int stateVar = 0;
}
```

```
function addToState(input){
  input.stateVar += 1
}

function main{
  data = new ClassWithState
  addToState(data)
  println(data.stateVar)
}
```

- Create a stack frame for the function call
- input is assigned the value in data
  - Which is a **memory address**

Memory Heap Example

Index	Value
...	...
63051	<Used by another program>
63052	commandLineArgs
63053	name:data, value:38772 (main)
63054	<function call stack frame>
63055	name:input, value:38772 (function)
63056	
63057	<Used by another program>
...	...

Index	Value
...	...
38772	ClassWithStateObject
38773	-stateVar value:1
38774	
...	...

```
class ClassWithState{
  int stateVar = 0;
}
```

```
function addToState(input){
  input.stateVar += 1
}

function main{
  data = new ClassWithState
  addToState(data)
  println(data.stateVar)
}
```

- Add 1 to input.state variable
- Find the object at memory address 38772
- Alter the state of the object at that address

Memory Heap Example

Index	Value
...	...
63051	<Used by another program>
63052	commandLineArgs
63053	name:data, value:38772 (main)
63054	
63055	
63056	
63057	<Used by another program>
...	...

Index	Value
...	...
38772	ClassWithStateObject
38773	-stateVar value:1
38774	
...	...

```
class ClassWithState{
  int stateVar = 0;
}
```

```
function addToState(input){
  input.stateVar += 1
}

function main{
  data = new ClassWithState
  addToState(data)
  println(data.stateVar)
}
```

- Function call ends
- Destroy all data in the stack frame
- input is destroyed
- Change to the object remains

Memory Heap Example

Index	Value
...	...
63051	<Used by another program>
63052	commandLineArgs
63053	name:data, value:38772 (main)
63054	
63055	
63056	
63057	<Used by another program>
...	...

Index	Value
...	...
38772	ClassWithStateObject
38773	-stateVar value:1
38774	
...	...

```
class ClassWithState{
  int stateVar = 0;
}
```

```
function addToState(input){
  input.stateVar += 1
}

function main{
  data = new ClassWithState
  addToState(data)
→ println(data.stateVar)
}
```

- Access data.stateVar
- Find the object at memory address 38772
- Access the state of the object at that address

Memory Heap Example

Index	Value
...	...
63051	<Used by another program>
63052	
63053	
63054	
63055	
63056	
63057	<Used by another program>
...	...

Index	Value
...	...
38772	
38773	
38774	
...	...

```
class ClassWithState{
  int stateVar = 0;
}
```

```
function addToState(input){
  input.stateVar += 1
}

function main{
  data = new ClassWithState
  addToState(data)
  println(data.stateVar)
}
```

- All memory freed when program ends

Debugger Example

Lecture Question

Question: In a package named "oop" create a Scala **class** named "Team" and a Scala **object** named "Referee".

Team will have:

- State values of type Int representing the strength of the team's offense and defense with a constructor to set these values. The parameters for the constructor should be offense then defense
- A third state variable named "score" of type Int that is not in the constructor, is declared as a **var**, and is initialized to 0

Referee will have:

- A method named "playGame" that takes two Team objects as parameters and return type Unit. This method will alter the state of each input Team by setting their scores equal to their offense minus the other Team's defense. If a Team's offense is less than the other Team's defense their score should be 0 (no negative scores)
- A method named "declareWinner" that takes two Teams as parameters and returns the Team with the higher score. If both Teams have the same score, return a new Team object with offense and defense both set to 0

Lecture Question

Sample Usage

```
val t1: Team = new Team(7, 3)
val t2: Team = new Team(4, 20)

Referee.playGame(t1, t2)
assert(Referee.declareWinner(t1, t2) == t2)
assert(Referee.declareWinner(t2, t1) == t2)
```

Commentary

We create Team as a **class** since we want to create many objects of type Team that will compete against each other. Each team will have different state (offense, defense, score), but will be the same type (Team)

Referee is an **object** since there only needs to be one of them and the object has no state. The same referee can officiate every game between any two teams

We pass **references** of objects of type Team to the Referee. Since the Referee has the references, when it changes the score of a Team that change is made to the state of that Team throughout the program