## Abstract Data Types

This lecture will

- Show how an abstract data type can be implemented as a Java class;
- Show how one class can be used by another;
- Introduce the **stack** data structure;
- Introduce the concept of a **wrapper class**, and the related concepts of **autoboxing** and **unboxing**.
- Look at a complicated design example

## A complex number class

- Complex numbers often arise in mathematics. They have the form $a + ib$, where $i = \sqrt{-1}$, $a$ is called the real part and $b$ is called the imaginary part.
- We want a class to represent complex numbers, so we consider a specification for the class:
- The variables are:

  `realPart` – the real part of a complex number

  `imagPart` – the imaginary part of a complex number

## Methods of the complex number class

- `getReal` – returns the real part
- `getImag` – returns the imaginary part
- `set` – sets the real and imaginary parts to the given values
- `setReal` – sets the real part to the given value
- `setImag` – sets the imaginary part to the given value
- `add`, `subtract`, `multiply`, `divide` – adds, subtracts multiplies and divides two complex numbers
- `conj`, `abs`, `angle`, – returns the complex conjugate, absolute value (magnitude) and angle (argument) respectively
- `copy` – returns a copy of the complex number
- `toString` – returns a string representing the complex number

Don't panic if you didn't do A Level maths. They are here just for completeness

## The `Complex` class – constructor

```
public class Complex {

   private double realPart;
   private double imagPart;

   /**
   * Creates an instance of the Complex class with
    * specified  values
   * @param   r      double       real part
   * @param   i      double       imaginary part
   */
   public Complex(double r, double i) {
      realPart = r;
      imagPart = i;
   }
```

## The Complex class – default constructor

```
public class Complex {
   private double realPart;
   private double imagPart;

   public Complex(double r, double i) {…}

   /**
   * Creates an instance of the Complex class with
    * default values
   */
   public Complex() {
      realPart = 0.0;
      imagPart = 0.0;
   }
```

## The Complex class – get methods

```
   /**
   * returns the real part of the complex number
   * @return double the real part of the complex number
   */
   public double getReal() {
      return realPart;
   }
   /**
   * returns the imaginary part of the complex number
   * @return double the imaginary part of the complex
   *                number
   */
   public double getImag() {
      return imagPart;
   }
```

## The Complex class – set methods

```
   /**
   * sets the value of a complex number
   * @param r double real part
   * @param i double imaginary part
   */
   public void set(double r, double i) {
      realPart = r;  imagPart = i;
   }
   /**
   * sets the real part of a complex number
   * @param r double real part
   */
   public void setReal(double r) {   realPart = r; }
   /**
   * sets the imaginary part of a complex number
   * @param i double imaginary part
   */
   public void setImag(double i) {   imagPart = i;    }
```

## The Complex class – add

```
/**
* returns the sum of the complex number and another
* complex number
* @param c    Complex  the complex number to add
* @return Complex     the sum of the complex numbers
*/
public Complex add(Complex c) {
   return new Complex(
       realPart+c.getReal(),
       imagPart+c.getImag());
}
```

## The Complex class – subtract

```
/**
* returns the difference between the complex number
* and another complex numbers
* @param c Complex  the complex number to subtract
* @return Complex   the difference of the complex
                    numbers
*/
public Complex subtract(Complex c) {
   return new Complex(
        realPart-c.getReal(),
        imagPart-c.getImag());
}
```

## The Complex class – multiply

```
/**
* works out the product of the complex number and
* another complex number
* @param c Complex  the complex number to multiply by
* @return Complex   the product of the complex numbers
*/
public Complex multipliedBy(Complex c) {
   return new Complex(
        realPart*c.getReal()-imagPart*c.getImag(),
        realPart*c.getImag()+imagPart*c.getReal());
}
```

## The Complex class – divide

```
/**
* works out the the complex number divided by another
* complex number
* @param c Complex  the complex number to divide by
* @return Complex   the division of two complex numbers
*/
public Complex dividedBy(Complex c) {

   double d = c.getReal()*c.getReal() +
              c.getImag()*c.getImag();

   return new Complex(
      (realPart*c.getReal()+imagPart*c.getImag())/d,
      (realPart*c.getReal()-realPart*c.getImag())/d);
}
```

## The Complex class – conjugate etc.

```
/**
* returns the complex conjugate
* @return Complex      the complex conjugate
*/
public Complex conj() {
   return new Complex(realPart,-imagPart);
}
/**
* returns the magnitude (modulus) of a complex number
* @return double       the magnitude (modulus)
*/
public double abs() {
   return Math.sqrt(realPart*realPart+imagPart*imagPart);
}
/**
* computes the argument (angle) of a complex number
* @return double       the argument (angle)
*/
public double angle(){
   return Math.atan(imagPart/realPart);
}
```

## The `Complex` class – `copy` and `toString`

```
/**
* returns a copy of a complex number
* @return Complex a copy of a complex number
*/
public Complex copy() {
   return new Complex(realPart,imagPart);
}
/**
* converts a complex number to a string for display
* @return String          a string representing the
*                         complex number
*/
public String toString() {
   if (  imagPart < 0.0  )
      return realPart+(imagPart+"i");
   else
      return realPart+"+"+imagPart+"i";
}
```

## Writing a test harness

- We provide a **`main`** method that reads a pair of complex numbers and tests each method of the **`Complex`** class.
- Note that **`Complex`** is not intended to be invoked directly by the Java interpreter (rather, instances of it will be created by other classes) – but by providing a **`main`** method we can now do so.
- This allows us to test the class in isolation before it is integrated into a larger system.

## The `Complex` class – test harness

```
public static void main(String args[]) {
   EasyReader keyboard = new EasyReader();
   do {

      // create two complex numbers
      // display the two numbers
      // test the accessor and mutator methods
      // test the operations on the numbers

   } while (keyboard.readBoolean("Another go?: "));

}
```

## Running the test harness (input in yellow)

```
> java Complex
First number:
Enter real part: 3
Enter imaginary part: -2
Second number:
Enter real part: 6
Enter imaginary part: 9
c1 = 3.0-2.0i
c2 = 6.0+9.0i
real part of c1 = 3.0
real part of c2 = 6.0
imaginary part of c1 = -2.0
imaginary part of c2 = 9.0
c1+c2 = 9.0+7.0i
c1-c2 = -3.0-11.0i
c1*c2 = 36.0+15.0i
c1/c2 = 0.0-0.07692307692307693i
abs(c1) = 3.605551275463989
abs(c2) = 10.816653826391969
conj(c1) = 3.0+2.0i
conj(c2) = 6.0-9.0i
angle(c1) = -0.5880026035475675
angle(c2) = 0.982793723247329

Another go?: n
```

## Implementation issues

- Note the way that mathematical expressions are formed:

```
Complex c1 = new Complex(2.4,1.3);
Complex c2 = new Complex(1.7,4.6);
Complex sum = c1.add(c2);
```

- We could also declare mathematical operations as class methods, rather than instance methods:

```
public static Complex add(Complex c1,Complex c2){
    return new Complex(c1.getReal()+c2.getReal(),
                       c1.getImag()+c2.getImag());
}
```

- Now we can write expressions like this:

```
sum = Complex.add(c1,c2);
```

## A stack class

- Stacks are useful in many computer science applications, such as writing compilers.
- Java actually provides a **`Stack`** class in the collections framework – however, it is instructive to see how to implement a stack for ourselves.
- A stack is characterised by the property that only the top element on the stack is accessible.

Image from Wikipedia

## Attributes and Methods of the `Stack` class

- We need the following attributes (class variables):

  **`items`** – a collection of elements that are the same type
  **`numElements`** – the number of elements on the stack

- And the following methods
  - **`isFull`** – returns true if the stack is full.
  - **`isEmpty`** – returns true if the stack is empty.
  - **`pop`** – removes an element from the top of the stack.
  - **`push`** – inserts an element on the top of the stack.
  - **`retrieve`** – returns a copy of the element on the top of the stack, without removing it.

## The `Stack` class – constructor etc.

```
public class Stack {
  //Constant - the maximum size of the Stack
  private static final int MAX_ITEM = 10;

  // instance variables
  private int numElements;
  private Object[] items;

  /*
  * Constructor
  * @returns a new, empty stack
  */
  public Stack() {
     numElements = 0;
     items = new Object[MAX_ITEM];
  }
```

See later

## The Stack class – isFull & isEmpty

```
/**
* Determines whether the Stack is full
* @return boolean   true if the Stack is full
*/
public boolean isFull() {
   return numElements==MAX_ITEM;
}

/**
* Determines whether the Stack is empty
* @return boolean true if the Stack is empty
*/
public boolean isEmpty() {
   return numElements==0;
}
```

## The Stack class – the pop method

```
/**
* Removes the element from the top
* Stops with an error if the stack is empty
* @return Object the element on the top of the
*                         Stack
*/
public Object pop() {
   if (  isEmpty()  ) System.exit(0);
   numElements-=1;
   return items[numElements];
}
```

## The Stack class – the push method

```
/**
* Puts an element on the top of the Stack
* The method stops with an error if the stack is
* full
* @param obj Object The thing to be added to the
*                         stack
*/
public void push(Object obj) {
   if (  isFull()  )  System.exit(0);
   items[numElements] = obj;
   numElements+=1;
}
```

## The Stack class – retrieve method

```
/**
* Returns a reference to the item on the top of
* the Stack
* The contents of the Stack are not changed
* @return Object the item on the top of the Stack
*/
public Object retrieve() {
  if (  isEmpty()  ) System.exit(0);
  return items[numElements-1];
}
```

## Test harness for the **Stack** class

```
public static void main(String args[]) {
   // variable declarations
   EasyReader keyboard = new EasyReader();
   Stack myStack = new Stack();

   // read five integers and push each onto the stack
   for (int i=0; i<5; i++) {
     int num=
          keyboard.readInt("Enter number "+(i+1)+": ");
     myStack.push(num);
   }

   // check the use of isEmpty and pop
   while (  !  myStack.isEmpty()  )
        System.out.println(  myStack.pop()  );
}
```

## Output of the test harness

- Typical run of test harness shown on the right, with user input in bold.
- Note that a stack is a **last-in first-out** (LIFO) data structure.
- Pushing a sequence of numbers onto the stack and then popping them off reverses their order.

```
>java Stack
Enter number 1: 5
Enter number 2: 4
Enter number 3: 3
Enter number 4: 2
Enter number 5: 1
1
2
3
4
5
```

## Implementation issues

- We defined the stack as an array of type **`Object`**:

```
   private Object[] items;
```

- All classes in Java are subclasses of the **`Object`** class; in other words, we can treat classes like **`String`** as "a kind of" **`Object`**.
- This is the concept of **inheritance** – see next term.
- We can make the stack more general if we just think of it as a stack of objects, rather than a stack of elements that have a specific type.

## A puzzle

- In the last program we wrote

```
   myStack.push(num);
```

but the signature for the push method is

```
   public void push(Object obj)
```

- Since **num** has type **`int`** we should expect a problem with type compatibility, since primitive types are not objects. So why is the compiler happy?
- The solution lies in **wrapper classes**, which act as object wrappers around primitive types.

## Wrapper types and autoboxing

- For every primitive type there is a corresponding wrapper class which represents a single value of that type, e.g. we could write

```
Integer objectNum = new Integer(num);
```

An instance method of `Integer`

- To get the **int** value back we could write

```
int numAgain = objectNum.intValue();
```

- But it is unnecessary, conversion of primitive types to the wrapper type is done automatically; this is called **autoboxing**. Wrapper types are also **unboxed** to the primitive type as required.

```
int numAgain = objectNum;
objectNum = 97;
```

## Wrapper classes

- All the basic types have wrapper classes

| Type | Wrapper |
|---|---|
| `byte` | `Byte` |
| `short` | `Short` |
| `int` | `Integer` |
| `long` | `Long` |
| `float` | `Float` |
| `double` | `Double` |
| `char` | `Character` |
| `boolean` | `Boolean` |

- You have been using their static methods

## Character static methods

`public static char toUpperCase(char ch)`
converts a **char** to upper case

`public static char toLowerCase(char ch)`
converts a **char** to lower case

`public static boolean isLowerCase(char ch)`
returns **true** if the **char** is lower case

`public static boolean isUpperCase(char ch)`
returns **true** if the **char** is upper case

`public static boolean isLetter(char ch)`
returns **true** if the **char** is a letter of either case

`public static boolean isDigit(char ch)`
returns **true** if the **char** is a digit

## Object-oriented design – a case study

- We will develop a Java program to play the Game of Life. A cellular automaton devised by Conway in 1970. See www.wikipedia.org for more information.
- We will use a simple OOD methodology based on Booch (1983). More advanced object-oriented design methodologies and notations will be covered in other modules.
- Go through the following steps:
  - Step 1: define the problem
  - Step 2: develop an informal strategy for solving the problem
  - Step 3: formalise the strategy

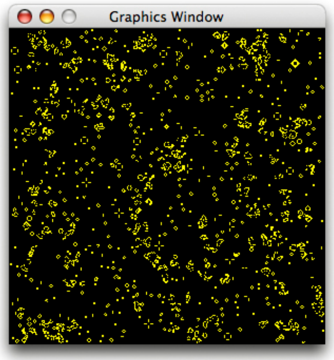
## The Game of Life - rules

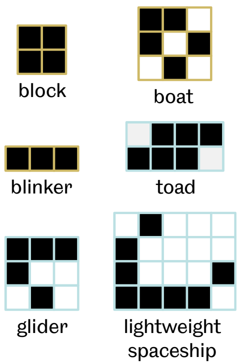
- The Game of Life takes place on a rectangular grid. The following simple rules are used to change the state of each location ('cell') in the grid:
  i. A cell is either empty (white) or alive (black).
  ii. Each cell is the centre of a 3 by 3 square grid of cells, which contains its eight neighbours.
  iii. An empty cell at time ***t*** becomes alive at time ***t+1*** if and only if three neighbouring cells were alive at time ***t***.
  iv. A cell that is alive at time ***t*** remains alive at time ***t+1*** if and only if either two or three neighbouring cells were alive at time ***t***. Otherwise, it dies for lack of company (<2) or overcrowding (>3).

## The game of life - implementation

- For simplicity, the borders of the grid are ignored (i.e., they cannot contain any living cells).
- A simulation starts with a random configuration of cells in the grid. At each time step, a new state for the grid is created from the previous state by applying the rules about becoming alive and staying alive and the new state of the grid is displayed.
- After several generations, interesting behaviour occurs such as the appearance of repeating life forms.
- The game is a cellular automaton devised by Conway in 1970. See www.wikipedia.org for more information.

## Output of the program




## Step 2: develop an informal strategy

- Write an informal description of the problem solution using terminology from the problem space.
- In this case, our strategy is quite close to the original problem description.

*The game of life takes place on a grid of pixels. At the start of the game, we initialise the grid by randomly setting each cell to be alive or dead. A new generation is then computed from the initial state by applying some simple rules. For each cell (but not cells at the edge of the grid), we determine how many of its neighbours are alive. We then use this information to set the value of the cell in the new state of the grid. The new state of the grid is displayed, and the old state is set to the new state. This process continues for the desired number of generations.*

## Step 3: formalise the strategy

- List the objects in the informal strategy. These correspond to **nouns**.
- List the methods (operations performed on objects) in the informal strategy. These correspond to **verbs**.
- Group together objects and methods into classes.
- This is usually an iterative process.

## Analysis of the problem description - nouns

- The **game of life** takes place on a **grid of pixels**. At the start of the game, we initialise the grid by randomly setting each cell to be alive or dead. A new **generation** is then computed from the initial **state** by applying some simple rules. For each **cell** (but not cells at the edge of the grid), we determine how many of its neighbours are alive. We then use this information to set the value of the cell in the new state of the grid. The new state of the grid is displayed, and the old state is set to the new state. This process continues for the desired number of **generations**.

## Analysis of the problem description - verbs

- The *game of life* takes place on a *grid of pixels*. At the start of the game, we **initialise the grid by randomly setting each cell** to be alive or dead. A new *generation* is then **computed** from the initial *state* by **applying some simple rules**. For each *cell* (but not cells at the edge of the grid), we **determine how many of its neighbours are alive**. We then use this information to **set the value of the cell** in the new state of the grid. The new state of the grid is **displayed**, and the **old state is set to the new state**. This process continues for the desired number of *generations*.

## Object-oriented design solution

- Possible classes: game of life, grid, generation, state, cell.
- Possible methods: initialise, compute new generation, apply rules, determine how many neighbours are alive, set the value of a cell, display the grid, set the old state to the new state.
- Discount inappropriate classes

game of life | grid | ~~generation~~

~~state~~ | cell ?

## Object-oriented design solution

- Possible classes: game of life, grid, generation, state, cell.
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- Discount inappropriate classes and group methods

game of life | grid | cell

initialise | compute new generation | apply rules | determine how many neighbours are alive | set the value of a cell | display the grid | set the old state to the new state

## Object-oriented design solution

- Possible classes: game of life, grid, generation, state, cell.
- Possible methods: initialise, compute new generation, apply rules, determine how many neighbours are alive, set the value of a cell, display the grid, set the old state to the new state.
- Discount inappropriate classes and group methods

game of life: initialise; Update state (compute new generation, set the old state to the new state)

grid: initialise; display the grid

cell: initialise; determine how many neighbours are alive; apply rules; set the value of a cell

## Writing classes with method stubs

- Start by writing the classes with instance variables and class constants, but **stubs** for the methods (empty method body).
- At this stage it emerges that it is necessary to have a `display` method in the `GameOfLife` class which will display the current state of the game; we expect this just to call a method that displays the grid.

## `GameOfLife` with method stubs

```
public class GameOfLife {
   private static final int MAX_GENERATIONS = 200;
   private static final int GRID_SIZE = 500;

   private Grid state;     // current grid state

   // constructor
   public GameOfLife() {}
   // initialise the game
   public void initialise() {}
   // update to the next generation
   public void updateState() {}
   // display the state of the grid
   public void display() {}
   // main method
   public static void main(String[] args) {}
}
```

## The Grid - choice of data structure

- The grid should be represented as a 2D array of cells which will contain only boolean values (since each cell has a binary value, alive/dead)
- Do we really need a cell class?
- To keep things general the constructor for the grid (and therefore the game) will allow the size of the grid to be specified

## Grid with method stubs

```
public class Grid {
   // the grid
   private boolean grid[][];

   // constructor, s is the size of the grid
   public Grid(int s) { grid = new boolean[s][s];}

   // set the cell at (i,j) to value b
   public void setCell(int i, int j, boolean b) { }
   // get the value of cell (i,j)
   public boolean getCell(int i, int j) { }
   // initialise the grid with random values
   public void initialise() { }
   // get the number of alive neighbours of (i,j)
   public int aliveNeighbours(int i, int j) { }
   // display
   public void display() { }
}
```

## Developing algorithms for methods

- Use top-down design to develop algorithms for methods.
- Algorithm for initialising the grid:

1. *Set the border cells to be dead*
2. *for each row i*
3. *for each column j*
4. *set the element at (i,j) to alive/dead with equal probability*

## The initialise method

```
public void initialise() {
   int gridSize = grid.length;
  //set the first and last row to be dead
   for  (int j=0; j<gridSize; j++)  {
     grid[0][j] = false;
     grid[gridSize-1][j] = false;
   }
   //the other rows should start and end with dead
  //but the cells in between have a 50% chance of
  //life
   for (int i=1; i<gridSize-1; i++) {
     grid[i][0] = false;
     grid[i][gridSize-1] = false;
     for (int j=1; j<gridSize-1; j++)
          grid[i][j]=Math.random()<0.5;
    }
}
```

## The `display` method

```
public void display(EasyGraphics g) {
   for (int i=0; i<grid.length; i++)
      for (int j=0; j<grid.length; j++) {
          if (  grid[i][j]  )
              g.setColor(255,255,0);
          else
              g.setColor(0,0,0);
          g.plot(i,j);
      }
}
```

## Finding the number of alive neighbours

- Algorithm:

1. *sum the number of alive neighbours in a 3x3 grid centred on (i,j)*
2. *if the element in the centre of the 3x3 grid is alive then*
   *subtract one from the sum*

- Step 1 refinement:

1.1 *set the sum to zero*
1.2 *for each row r between i-1 and i+1*
1.3 *for each column c between j-1 and j+1*
1.4 *if the element at (r,c) is alive then*
1.5 *add one to the sum*

## The `aliveNeighbours` method

```
public int aliveNeighbours(int i, int j) {
   int sum=0;
   for (int r=-1; r<=1; r++)
     for (int c=-1; c<=1; c++)
       if (grid[i+r][j+c]) sum++;
   if (grid[i][j]) sum--;
   return sum;
}
```

- Writing `get` and `set` methods is easy.
- We also provide a test harness (`main` method) which enables us to test the `Grid` class independently.

## Completed `Grid` class (1)

```
import sheffield.*;
public class Grid {

   private boolean grid[][];

   public Grid(int gridSize) {
     grid = new boolean[gridSize][gridSize];
   }

   public boolean getCell(int i, int j) {…}
   public void setCell(int i, int j, boolean b) {…}
   public int getGridSize() {…}
   public void initialise() {…}
   public int aliveNeighbours(int i, int j) {…}
   public void display(EasyGraphics g) {…}
```

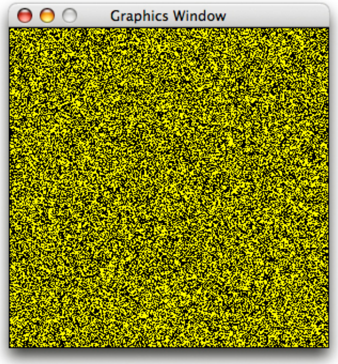
## Completed `Grid` class (2)

```
   public static void main(String[] args) {
     final int GRID_SIZE = 300;
     EasyGraphics g = new
                  EasyGraphics(GRID_SIZE,GRID_SIZE);
     Grid grid = new Grid(GRID_SIZE);
     grid.initialise();
     grid.display(g);
   }
}
```

- We can test the **`Grid`** class independently:

```
>javac Grid.java
>java Grid
```

## Output of the `Grid` test harness




## The `GameOfLife` class

- Top-level algorithm:

1. *initialise the grid to have random contents*
2. *for each generation*
3. *display the grid in the graphics screen*
4. *update the grid using the rules*

- This gives us the **`main`** method:

```
public static void main(String[] args) {
   GameOfLife game = new GameOfLife(GRID_SIZE);
   game.initialise();
   for (int i=0; i<MAX_GENERATIONS; i++) {
      game.display();
      game.updateState();
   }
}
```

## The `GameOfLife` constructor

- The constructor is straightforward; we just need an old and new grid state, and a graphics window:

```
public class GameOfLife {

   private static final int MAX_GENERATIONS = 200;
   private static final int GRID_SIZE = 500;

   private Grid state;
   private EasyGraphics graphics;

   public GameOfLife(int size) {
      state = new Grid(size);
      graphics = new EasyGraphics(size, size);
   }
   ……
}
```

## Initialising & displaying the game state

- To initialise the game we set the grid to an initial random state:

```
public void initialise() {
   state.initialise();
}
```

- To display the game state, we just call the display method of the grid:

```
public void display() {
   state.display(graphics);
}
```

## Updating the game state – algorithm

1. *compute the new grid state by applying the neighbourhood rules to the old state*
2. *copy the new grid state into the old grid state*

Should we have given Grid a copy method?

**Step 1 refinement**

1.1 *for each row i*
1.2 *for each column j*
1.3 *find the number of alive neighbours around (i,j) in the old grid*
1.4 *if number of alive neighbours is 3*
1.5 *set (i,j) in the new grid state to alive*
1.6 *else if number of alive neighbours is 2 and (i,j) is alive in the old grid*
1.7 *set (i,j) in the new grid state to alive*
1.8 *else*
1.9 *set (i,j) in the new grid state to dead*

## The `updateState` method

```
public void updateState() {
   // compute the new grid state by applying the
   // neighbourhood rules to the old state

   Grid newState = new Grid(GRID_SIZE);
   for (int i=1; i<GRID_SIZE-1; i++)
      for (int j=1; j<GRID_SIZE-1; j++) {

         int num = state.aliveNeighbours(i,j);
         newState.setCell(i,j,
              num==3 ||
                 (state.getCell(i,j) && num==2) );
      }

   // copy the new grid state into the old grid state
   for (int i=1; i<GRID_SIZE-1; i++)
      for (int j=1; j<GRID_SIZE-1; j++) {
         state.setCell(i,j,newState.getCell(i,j));
}
```

## Completed `GameOfLife` class

```
public class GameOfLife {
   private static final int MAX_GENERATIONS = 200;
   private static final int GRID_SIZE = 500;
   private Grid state;
   private EasyGraphics graphics;
   public GameOfLife(int size) {…}
   public void updateState() {…}
   public void initalise() {…}
   public void display(EasyGraphics g) {…}

   public static void main(String[] args) {
      GameOfLife g = new GameOfLife(300);
      g.initialise();
      for (int i=0; i<MAX_GENERATIONS; i++) {
           g.display();
           g.updateState();
      }
   }
}
```

## Looking back

- Could we have done anything better or differently?
- The screen update using the `EasyGraphics` plot method is slow; much better performance could be obtained using the Swing API directly.
- Does the `updateState` method belong in `GameOfLife`? Should it be in `Grid`?
- Or in the potential class we didn't use, `Cell`?

## Summary of key points

- We should write classes with **reuse** in mind
- We should provide a **test harness** for a new Java class; writing a `main` method is a convenient way of doing this
- When writing a new class, think first about the **specification** for the class (the data it holds and the operations it provides)
- We only think about the **implementation** issues when we have a clear specification of the class
- Using constants and the `Object` class rather than something specific can make classes more general