

# Advanced Math and Functional Programming

Dr. Jim Newton

June 7, 2022

# MGS 2022: Creating a Culture of Belonging

applications open November 1 - 30, 2021

## Bias, Inclusion, Belonging

Mathematics is unbiased. It is one of the few pursuits which is free of politics, nationality, religion, gender, sexuality, age, race, handicap, or of anything else that so often divides us.

# Overview

- 1 Introduction
- 2 Environment
- 3 Sets and Functions
- 4 Looping
- 5 Abstract Algebra
- 6 Analysis

# Objectives

Mathematics: Ameliorate your love for Mathematics.

Computer Science: Develop a sense of functional programming.

Communication: Confidently defend your ideas.

# Tactic

- Theory — Learn mathematics and computer science concepts.
- Practice — Create code relating to the theory of various units.

# Ambitious Syllabus

Week	Day	Unit	Activities
1	Mon	0, 1	Environment Set-up, Hello World
	Tue	2	Sets and Functions, Theory, First Program
	Wed	2	Coding Exercises, Presentation
	Thu	3	Abstract Algebra, Theory
	Fri	3	Group Project, Coding Exercises
2	Mon	3	Review, Coding Exercises
	Tue	4,5	Analysis: Convergence, and Sums
	Wed	4,5	Coding Exercises, Presentation
	Thu	6,7	Analysis: Derivative, Integral
	Fri	6,7	Coding Exercises, Presentation

# Setup the Environment

## Create GitHub Account

Create a GitHub account using an abstract user name.

Don't use your real name.

Open: <https://github.com/join>

# GitHub Project

Open: <https://github.com/jimka2001/mgs-2022>

# Fork the Repository

A screenshot of a GitHub repository page. At the top, there is a dark header bar with the GitHub logo, a search bar containing "Search or jump to...", and navigation links for Pulls, Issues, Marketplace, and Explore. To the right of the header are icons for notifications, a plus sign, and user profile. Below the header, the repository name "jimka2001/mgs-2022" is displayed in blue, followed by the word "Public". To the right of the repository name are three buttons: "Watch 1", "Fork 1", and "Star 0". At the bottom of the header, there is a navigation bar with links for Code, Issues, Pull requests, Actions, Projects, Wiki, Security, and three vertical dots for more options.

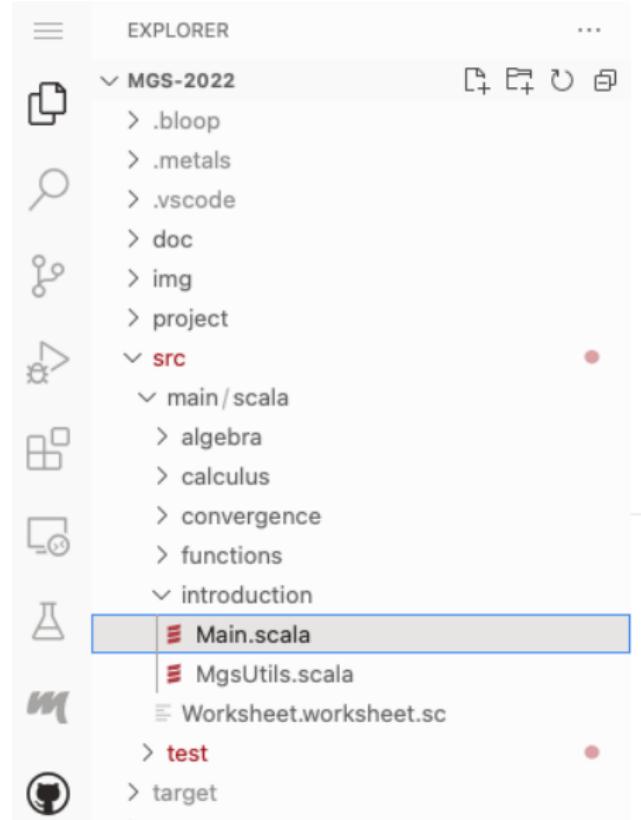
## Open the GitPod Workspace

Prepend

**http://gitpod.io/#**

to the URL already in the web browser.

# Open Main.scala

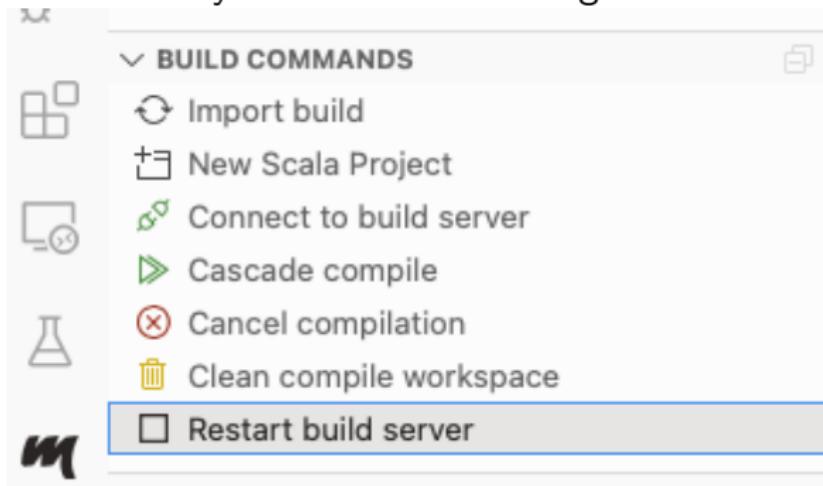


## Ready to edit and run

```
>Main.scala ×  
src > main > scala > introduction > Main.scala > {} introduction  
1 package introduction  
2  
    run | debug  
3 ✓ object Main {  
4  
    5     def main(args: Array[String]): Unit = {  
    6         println("hello world")  
    7         println("")  
    8     }  
    9 }  
10
```

# Build Server

You may need to restart the guild-server.



# Understanding the Development Flow

## Text Files

Classical learning  
curves for some  
common editors



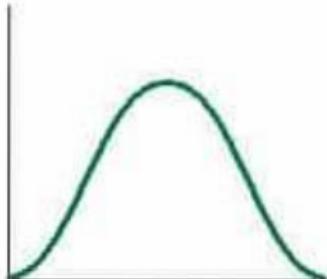
Notepad



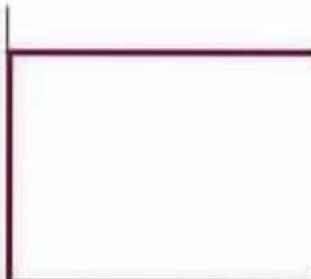
Pico



Visual Studio



vi



emacs



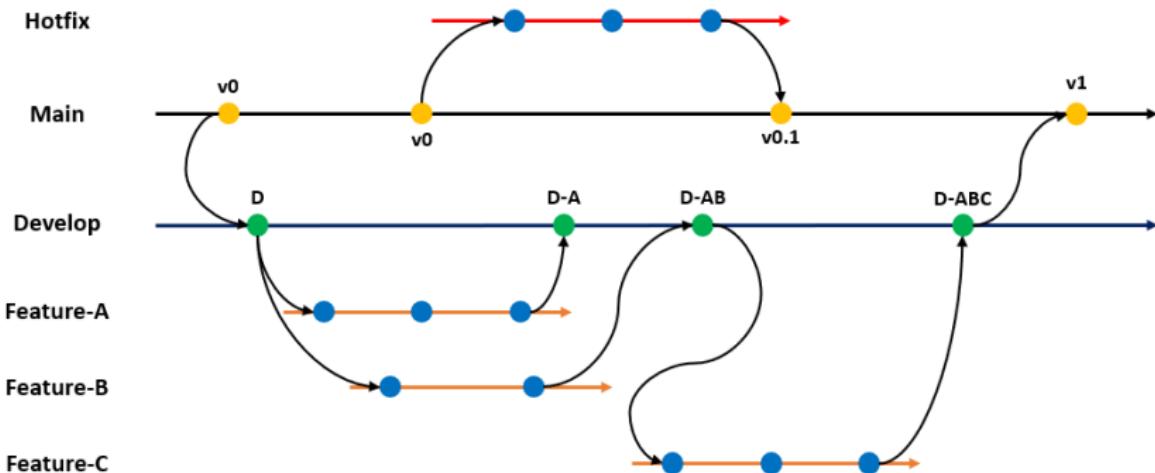
# VS Code

The screenshot shows the Visual Studio Code (VS Code) interface. The top navigation bar includes icons for File, Edit, D, O, P, P, Main.scala, O, G, G, and G. The left sidebar (Explorer) displays the project structure under 'MGS-2022': .metals, .vscode, img, project, src (with main/scala expanded to show AbstractAlgebra.scala, Convergence.scala, DifferentialCalculus.scala, InfiniteSums.scala, IntegralCalculus.scala, Main.scala, MgsUtils.scala, SetsAndFunctions.scala, Worksheet.worksheet.sc), test, target, .gitignore, .gitpod.yml, .jvmopts, .scalafmt.conf, build.sbt, gitpod\_command.sh, gitpod\_init.sh, README.md, OUTLINE, and TIMELINE. The main editor area shows the file 'Main.scala' with the following code:

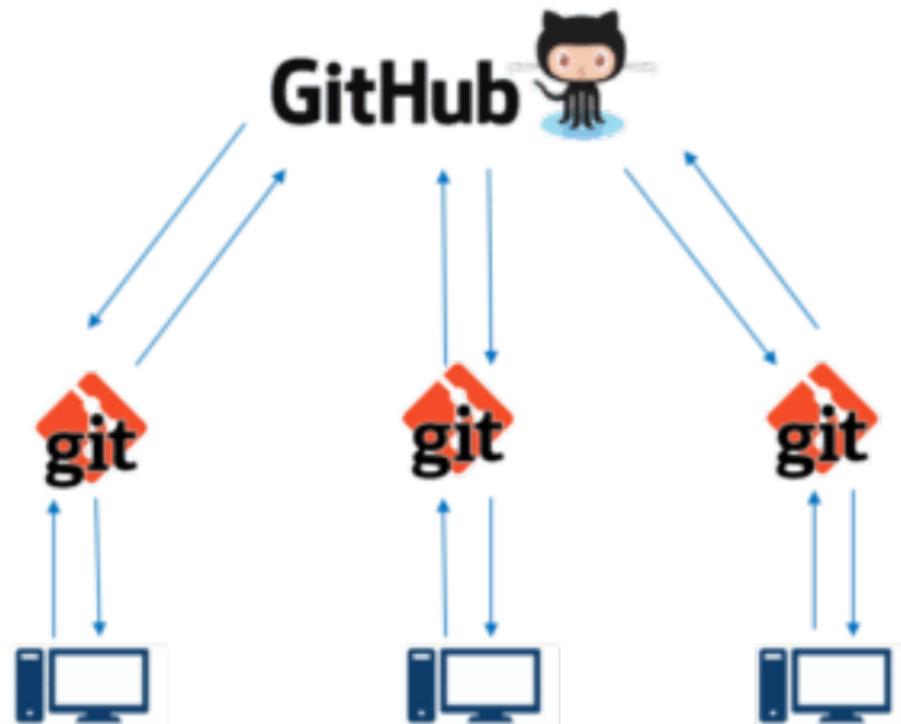
```
1 // Permission is hereby granted, free of charge, to any person
2 // a copy of this software and associated documentation
3 // files (the "Software"), to deal in the Software without res-
4 // including without limitation the rights to use, copy, modify,
5 // publish, distribute, sublicense, and/or sell copies of the S-
6 // and to permit persons to whom the Software is furnished to do
7 // subject to the following conditions:
8 //
9 // The above copyright notice and this permission notice shall
10 // be included in all copies or substantial portions of the Softw
11 //
12 // THE SOFTWARE IS PROVIDED "AS IS", WITHOUT WARRANTY OF ANY K
13 // EXPRESS OR IMPLIED, INCLUDING BUT NOT LIMITED TO THE WARRAN
14 // MERCHANTABILITY, FITNESS FOR A PARTICULAR PURPOSE AND
15 // NONINFRINGEMENT. IN NO EVENT SHALL THE AUTHORS OR COPYRIGHT
16 // LIABLE FOR ANY CLAIM, DAMAGES OR OTHER LIABILITY, WHETHER IN
17 // OF CONTRACT, TORT OR OTHERWISE, ARISING FROM, OUT OF OR IN C
18 // WITH THE SOFTWARE OR THE USE OR OTHER DEALINGS IN THE SOFTW
19
20 object Main {
21
22     def main(args: Array[String]): Unit = {
23         println("hello world")
24         println("")
25     }
26 }
```

The status bar at the bottom shows: Gitpod, main, 0 ▲ 0, Git Graph, Share, Ln 1, Col 1, Spaces: 2, UTF-8, LF, Scala, Layout: U.S., Ports: 33895, 8212, and a refresh icon.

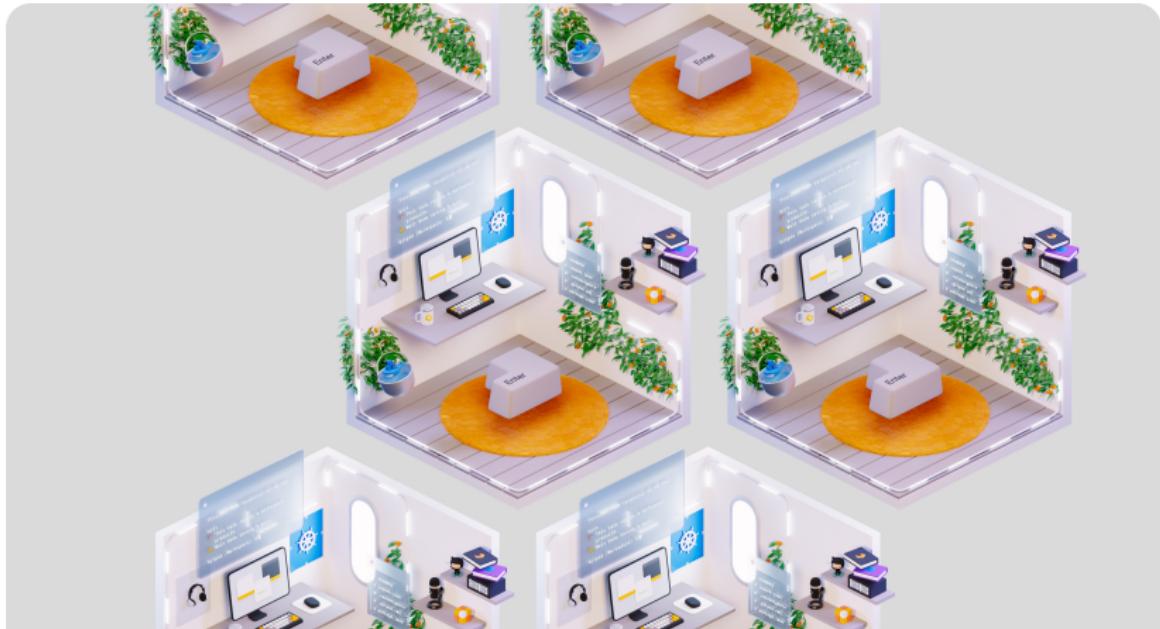
# Version Control



# git and GitHub

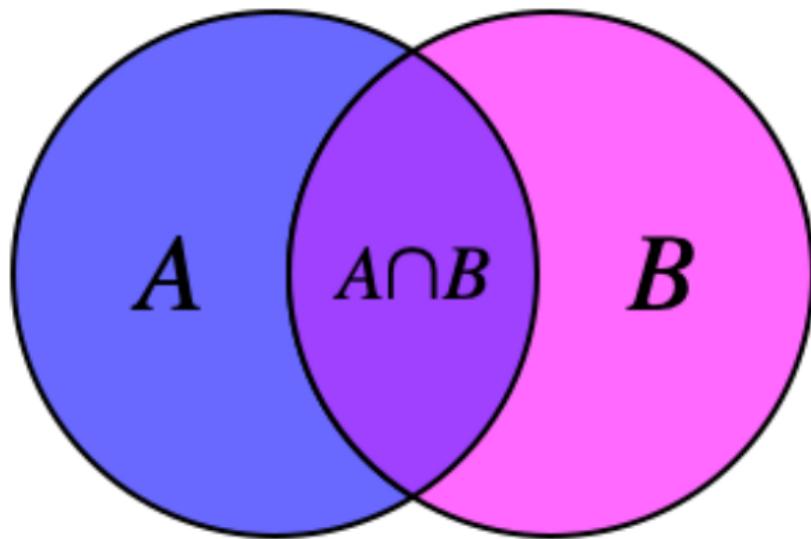


# GitPod



# Sets and Functions

What is a set?



## What is a set?

We won't really answer this question, because it is *too complicated*.

We will rely on intuition.

For more information see: Zermelo–Fraenkel Set Theory (ZF or ZFC).

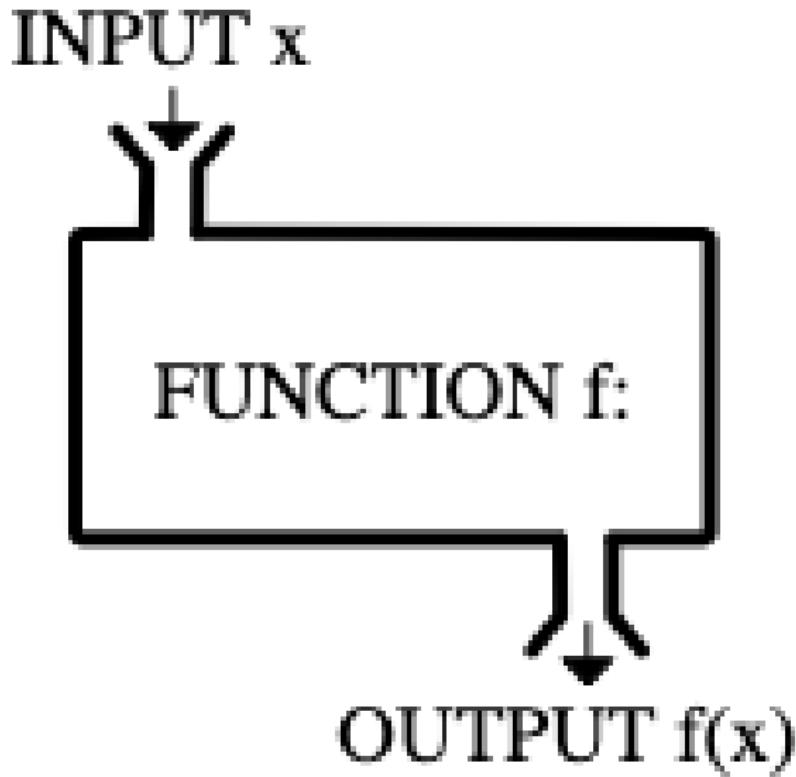
YouTube: Axioms of set Theory – Lecture 2, Frederic Schuller

## Some Important Sets

- $\mathbb{N}$  — natural numbers
- $\mathbb{Z}$  — integers
- $\mathbb{Q}$  — rational numbers
- $\mathbb{R}$  — real numbers
- $\mathbb{R}^2$  — ordered pairs of real numbers
- $\mathbb{C}$  — complex numbers

# What is a function?

## What is a function?



# What is a function?

You may already have some intuition about functions.

- A functions may have a name: sin, cos, and log.
- A function may lack a name:  $\frac{x^2-1}{x^2+2x+1}$ .

# What is a function?

## Definition (function)

A *function*,  $f$ , with domain  $X$  and range  $Y$ , denoted

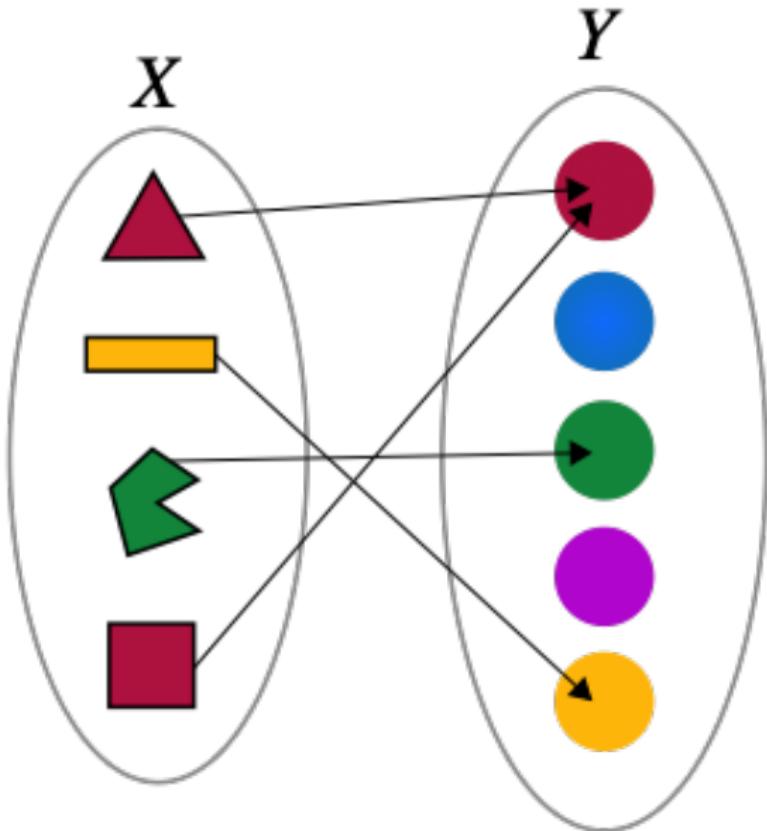
$$f : X \rightarrow Y$$

is a correspondence between two sets.

If  $x \in X$ , then  $f(x)$  designates a unique, well-determined, element of  $Y$ .

$$x \in X \implies f(x) \in Y.$$

## Correspondence between sets



## Examples of Functions

$$f(x) = 3x + 1$$

$f : \mathbb{N} \rightarrow \mathbb{N}$  by  $f(x) = 3x + 1$

Domain and range may be different

$$f : \mathbb{R}^2 \rightarrow \mathbb{R} \text{ by } f(x, y) = 3x - 2y + 1$$

## Functions defined by cases

$$|x| = \begin{cases} x & ; \text{if } x > 0 \\ 0 & ; \text{if } x = 0 \\ -x & ; \text{if } x < 0 \end{cases}$$

## Functions defined by recurrence

$$m^n = \underbrace{m \times m \times \dots \times m}_{n \text{ times}}$$

$$m^n = \begin{cases} 1 & ; \text{if } n = 0 \\ m \times m^{n-1} & ; \text{if } n > 0 \\ \frac{1}{m^{-n}} & ; \text{if } n < 0 \text{ and } m \neq 0 \end{cases}$$

## Functions defined by recurrence

$$n! = 1 \times 2 \times \dots \times n$$

$$n! = \begin{cases} 1 & ; \text{if } n = 0 \\ n \times (n - 1)! & ; \text{if } n > 0 \end{cases}$$

## Fibonacci numbers by recurrence

$$F(n) = \begin{cases} 1 & ; \text{if } n = 1 \\ 1 & ; \text{if } n = 2 \\ F(n - 1) + F(n - 2) & ; \text{if } n > 2 \end{cases}$$

## Subsets of size $n$

$$\mathbb{P}_n(S) = \begin{cases} \{\emptyset\} & ; \text{if } n = 0 \\ \{\{x\} \cup y \mid x \in S, y \in \mathbb{P}_{n-1}(S \setminus \{x\})\} & ; \text{if } n > 0 \end{cases} \quad (1)$$

Equivalently

$$\mathbb{P}_n(S) = \begin{cases} \{\emptyset\} & ; \text{if } n = 0 \\ \bigcup_{x \in S} \{\{x\} \cup y \mid y \in \mathbb{P}_{n-1}(S \setminus \{x\})\} & ; \text{if } n > 0 \end{cases} \quad (2)$$

# Looping

## Why do we need loops?

- to do something
- to collect something
- to detect something

# Why do we need loops?

- to do something
  - `for`
- to collect something
  - `for + yield`
- to detect something
  - `exists` and `forall`

## Simple loops

Construct simple loops with `for`.

```
for{ x <- List(10,20,30,40)
    } println(x)
```

```
for{ x <- Set(10,20,30,40)
    } println( x * x )
```

## Concentric loops

We can put loops inside loops, and we can use **List**, **Vector**, **Set** etc.

```
for{ x <- Set(10,20,30,40)
      y <- Vector(5,6,7)
    } println(x + y)
```

## Build collections by looping

Add the keyword `yield` to collect results.

```
for{ x <- Set(10,20,30,40)
      y <- Vector(5,6,7)
} yield x + y
```

## Loops with conditionals

Use `if` to filter out certain iterations.

```
for{ x <- Set(10,20,30,40)
      y <- Vector(5,6,7)
      if x + y < 30
    } yield x + y
```

## Loops with temporary variables

Use `=` to capture intermediate values

```
for{ x <- Set(10,20,30,40)
      y <- Vector(5,6,7)
      z = x + y
      if z > 21
    } yield x + y
```

## Loops combining multiple things

```
for{ x <- set1
    y <- set2
    if y + x < 100
    z <- set3
    w = fibonacci(x + y)
    if w < factorial(z)
} println(List(x,y,z,w))
```

## Boolean valued loops

Use `exists` to detect whether *at least one* value in a collection meets some condition: matches a *predicate*

```
Set(10,20,30,31,32).exists{  
    x => x < 0  
}
```

```
Set(10,20,30,31,32).exists{  
    x => x % 2 == 1  
}
```

## Boolean valued loops

Use `forall` to detect whether *every* value in a collection meets some condition: matches a *predicate*

```
Set(10,20,30,31,32).every{  
    x => x > 0  
}
```

```
Set(10,20,30,31,32).exists{  
    x => x % 2 == 0  
}
```

## Looping between bounds

Use `to` create a collection of integers in a `Range`.

```
(0 to 10).forall{  
    x => factorial(x) < 100  
}
```

```
(1 to 100 by 2).exists{  
    x => x * x == 64  
}
```

```
for{ n <- 1000 to 1 by -3  
    if n % 2 == 0  
} print(n)
```

```
for{ n <- 2 to 1000  
    if n % 2 == 0  
} yield n
```

## Concentric Boolean loops

```
(1 to 100).exists{  
    a => List(1,2,3,4).forall{  
        b => a*a + b*b > 100  
    }  
}
```

## Challenging exercises

- ① Collect all prime numbers between  $n$  and  $m$ .
- ② Collect all Pythagorean triples between 1 and  $n$ .
- ③ Find (print or collect) all solutions to  $a^3 + b^3 + c^3 = 1$  for  $a, b, c$  in range of  $-n$  to  $n$ .
- ④ Taxi cab numbers: For a given  $n$ , find numbers between  $-n$  and  $n$  which are the sum of two cubes in two different ways. E.g.,  
 $1729 = 12^3 + 1^3 = 9^3 + 10^3$ .
- ⑤ Linear Diophantine Equation: Given integers  $a$ ,  $b$ ,  $c$ , and  $n$ , find all (positive) integer solutions to the equation  $ax + by = c$ . Extend the function to support positive and negative number. E.g.,  $2x + 4y = 28$  has  $x = 12$ ,  $y = 1$  as solution but also  $x = 2$ ,  $y = 6$ .

## Instructions

- ① Choose one challenge:
- ② Work as individual or team.
- ③ Create a new file in the `functions` directory.
- ④ Try to solve it using `for`, `yield`, `exists`, and `forall`.
- ⑤ When finished and working, submit a *pull request*
- ⑥ Show, explain, and defend your solution to your fellow scholars.

# Abstract Algebra

## Finding roots of polynomial

If

$$ax^2 + bx + c = 0, a \neq 0$$

then

$$x_{1,2} = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}.$$

What about higher order polynomials?

Given the roots, we can *easily* find the coefficients.

Simply multiply

$$(x - r_1)(x - r_2) \dots (x - r_n)$$

to arrive at

$$x^n + \dots + a_2x^2 + a_1x^1 + a_0$$

However, given the coefficients, it is extremely difficult to find the roots.

# Story of Evariste Galois



Le Ciel de Leyenda

# Story of Evariste Galois



## Story of Evariste Galois



# Monoid

i

## Definition (Monoid)

$(S, \circ)$  is called a *monoid* if

- ① Closure:  $a, b \in S \implies a \circ b \in S$ .
- ② Associative:  $a, b, c \in S \implies (a \circ b) \circ c = a \circ (b \circ c)$
- ③ Identity:  $\exists e \in S$  such that  $a \in S \implies a \circ e = e \circ a = a$

## Examples of monoid

- $(\mathbb{N}, +)$ , the set of natural numbers under addition is a monoid.
- $(\mathbb{Z}, -)$ , the set of integers under subtraction is NOT a monoid. Why?
- The set of even integers under addition is a monoid.
- The set of even integers under multiplication is a NOT monoid. Why?
- $(\mathbb{R}^+, \times)$ , the set of positive real numbers under multiplication is a monoid.

## Examples of monoid

- The set of  $2 \times 3$  matrices under addition is a monoid.
- The set of  $2 \times 3$  matrices under multiplication is not a monoid. Why?
- However the set of  $3 \times 3$  matrices under multiplication is a monoid.

## Examples of monoid

- The set of subsets of a given set using the operation of union is a monoid. What is the identity element?
- The set of subsets of a given set using the operation of intersection is a monoid. What is the identity element?

## The free monoid

Let  $\Sigma = \{a, b, c, d\}$ .

The set,  $\mathcal{L}(\Sigma)$ , of all sequences of finite length  $(x_1, x_2, \dots, x_n)$  for which  $x_i \in \Sigma$  for  $i = 1, 2, \dots, n$ ,  $n \geq 0$ .

Let  $+$  denote sequence concatenation. *E.g.*,

$$(a, c, a, a) + (d, a, c, a, b) = (a, c, a, a, d, a, c, a, b).$$

$\mathcal{L}(\Sigma)$  is a monoid.

What is its identity element?

Is it a commutative monoid?

## Clock addition

The integers,  $\{1, 2, 3, \dots, 12\}$  form a additive monoid.

+	1	2	3	4	5	6	7	8	9	10	11	12
1	2	3	4	5	6	7	8	9	10	11	12	1
2	3	4	5	6	7	8	9	10	11	12	1	2
3	4	5	6	7	8	9	10	11	12	1	2	3
4	5	6	7	8	9	10	11	12	1	2	3	4
5	6	7	8	9	10	11	12	1	2	3	4	5
6	7	8	9	10	11	12	1	2	3	4	5	6
7	8	9	10	11	12	1	2	3	4	5	6	7
8	9	10	11	12	1	2	3	4	5	6	7	8
9	10	11	12	1	2	3	4	5	6	7	8	9
10	11	12	1	2	3	4	5	6	7	8	9	10
11	12	1	2	3	4	5	6	7	8	9	10	11
12	1	2	3	4	5	6	7	8	9	10	11	12

## Clock multiplication

The integers,  $\{1, 2, 3, \dots, 12\}$  form a multiplicative monoid.

*	1	2	3	4	5	6	7	8	9	10	11	12
1	1	2	3	4	5	6	7	8	9	10	11	12
2	2	4	6	8	10	12	2	4	6	8	10	12
3	3	6	9	12	3	6	9	12	3	6	9	12
4	4	8	12	4	8	12	4	8	12	4	8	12
5	5	10	3	8	1	6	11	4	9	2	7	12
6	6	12	6	12	6	12	6	12	6	12	6	12
7	7	2	9	4	11	6	1	8	3	10	5	12
8	8	4	12	8	4	12	8	4	12	8	4	12
9	9	6	3	12	9	6	3	12	9	6	3	12
10	10	8	6	4	2	12	10	8	6	4	2	12
11	11	10	9	8	7	6	5	4	3	2	1	12
12	12	12	12	12	12	12	12	12	12	12	12	12

# What is a group?

## Definition (Group)

$(S, \circ)$  is called a *group* if

- ①  $(S, \circ)$  is a monoid.
- ② Inverse:  $\forall a \in S \exists a^{-1} \in S$  such that  $a \circ a^{-1} = a^{-1} \circ a = e$

If  $a \circ b = b \circ a$  for all  $a, b \in S$ , then we call  $S$  an *Abelian* group.

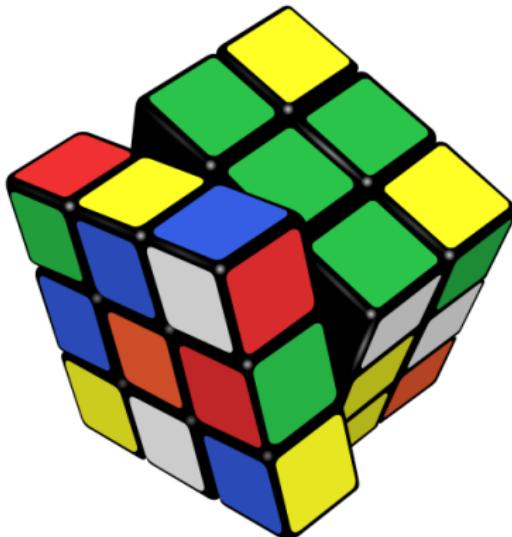
## Examples of group

- The set of integers,  $\mathbb{Z} = \{0, \pm 1, \pm 2, \dots\}$ , is a group under integer addition. Why?
  - $(\mathbb{Z}, +)$  is a monoid with 0 being the identity.
  - If  $a \in \mathbb{Z}$  there exists  $b \in \mathbb{Z}$  such that  $a + b = 0$ . E.g.,  $12 + (-12) = 0$
- The integers under multiplication is not a group. Why?

## Examples of group

Is the set of rotations of the Rubik's cube a group?

If so, what is the identity, and what are the inverses?



## Examples of group

Is the set of  $3 \times 3$  matrices of real numbers is a group.

Why? or Why not?

## Examples of group

- Is the set of subsets of a given set,  $G$ , using the operation of union a group. Why? Why not?
- The set subsets of a given set,  $G$ , using

$$A \circ B = (A \cap \overline{B}) \cup (\overline{A} \cap B)$$

as the operation, is a group.

- Every element is its own inverse.
- The identity element is the empty set,  $\emptyset$ .

# Clock multiplication

The 11-clock

*	1	2	3	4	5	6	7	8	9	10	11
1	1	2	3	4	5	6	7	8	9	10	11
2	2	4	6	8	10	1	3	5	7	9	11
3	3	6	9	1	4	7	10	2	5	8	11
4	4	8	1	5	9	2	6	10	3	7	11
5	5	10	4	9	3	8	2	7	1	6	11
6	6	1	7	2	8	3	9	4	10	5	11
7	7	3	10	6	2	9	5	1	8	4	11
8	8	5	2	10	7	4	1	9	6	3	11
9	9	7	5	3	1	10	8	6	4	2	11
10	10	9	8	7	6	5	4	3	2	1	11
11	11	11	11	11	11	11	11	11	11	11	11

## Examples of group

The non-11 elements of the 11-clock

*	1	2	3	4	5	6	7	8	9	10
1	1	2	3	4	5	6	7	8	9	10
2	2	4	6	8	10	1	3	5	7	9
3	3	6	9	1	4	7	10	2	5	8
4	4	8	1	5	9	2	6	10	3	7
5	5	10	4	9	3	8	2	7	1	6
6	6	1	7	2	8	3	9	4	10	5
7	7	3	10	6	2	9	5	1	8	4
8	8	5	2	10	7	4	1	9	6	3
9	9	7	5	3	1	10	8	6	4	2
10	10	9	8	7	6	5	4	3	2	1

# What is a ring?

## Definition (Ring)

$(S, +, \times)$  is called a *ring* if

- ①  $(S, +)$  is an Abelian group.
- ②  $(S, \times)$  is a monoid.
- ③ Distributive:  $a, b, c \in S \implies a \times (b + c) = (a \times b) + (a \times c)$ .

## Examples of ring

- The integers  $(\mathbb{Z}, +, \times)$  is a ring.
- The integers  $(\mathbb{N}, +, \times)$  is not a ring. Why?
- The set of  $n \times n$  matrices, for a fixed value of  $n > 0$  is a ring.
- The set of  $2 \times 3$  matrices is not a ring. Why?

## Examples of ring

- $\mathbb{Z}[x]$ , polynomials with integer coefficients such as  $3x^4 + 2x^2 - 5x + 1$ ?
- $\mathbb{R}[x]$ , polynomials with real coefficients such as  $3x^4 + \pi x^2 - ex + \sqrt{5}$ ?
- The *normalized* subset of  $\mathbb{Q}[x]$  with leading coefficient equal to 1?
  - Under *ordinary* addition and multiplication?
  - Can you define an alternative addition and multiplication which makes  $S$  a ring?

# What is a field?

## Definition (Field)

$(F, +, \times)$  is called a *field* if

- ①  $(F, +, \times)$  is an Abelian Ring.
- ②  $(F \setminus 0, \times)$  is a (Abelian) group, where 0 is the identity under +.

## Examples of field

- ① The rational numbers,  $\mathbb{Q}$ ?
- ② The set of  $n \times n$  matrices?
- ③ The set of  $2 \times 2$  matrices of the form  $\begin{bmatrix} a & -b \\ b & a \end{bmatrix}$  where  $a, b \in \mathbb{Q}$ ?
- ④ The complex numbers
- ⑤ The integers modulo 12?

## Examples of field

The integers modulo any prime such as 7?

+	0	1	2	3	4	5	6
0	0	1	2	3	4	5	6
1	1	2	3	4	5	6	0
2	2	3	4	5	6	0	1
3	3	4	5	6	0	1	2
4	4	5	6	0	1	2	3
5	5	6	0	1	2	3	4
6	6	0	1	2	3	4	5

×	0	1	2	3	4	5	6
0	0	0	0	0	0	0	0
1	0	1	2	3	4	5	6
2	0	2	4	6	1	3	5
3	0	3	6	2	5	1	4
4	0	4	1	5	2	6	3
5	0	5	3	1	6	4	2
6	0	6	5	4	3	2	1

## Review of algebraic structures

- ① A *monoid* is a set where we can add.
- ② A *group* is a set where we can add and subtract.
- ③ A *ring* is a set where we can add, subtract, and multiply.
- ④ A *field* is a set where we can add, subtract, multiply, and divide.

## Fast Power (exponentiation)

Which algebraic structures can we use these equations?

$$x^n = \begin{cases} e & ; \text{if } n = 0 \\ x & ; \text{if } n = 1 \\ x \circ x^{n-1} & ; \text{if } n \text{ is odd} \\ (x^{\frac{n}{2}}) \circ (x^{\frac{n}{2}}) & ; \text{if } n \text{ is even} \end{cases} \quad (3)$$

$$x^n = \begin{cases} e & ; \text{if } n = 0 \\ x & ; \text{if } n = 1 \\ x \circ x^{n-1} & ; \text{if } n > 0 \text{ is odd} \\ (x^{\frac{n}{2}}) \circ (x^{\frac{n}{2}}) & ; \text{if } n > 0 \text{ is even} \\ (x^{-1})^{|n|} & ; \text{if } n < 0 \end{cases} \quad (4)$$

# Convergence

# Infinite Sums