CS4400/5400
Programming λanguages

Spring 2024

Instructor: Steven Holtzen

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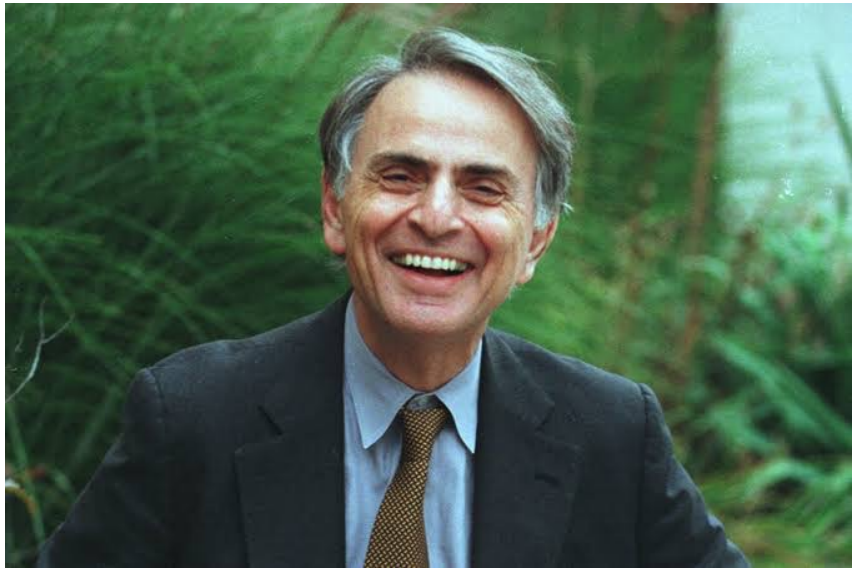
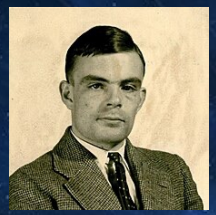
Northeastern University
Khoury College of Computer
and Information Sciences

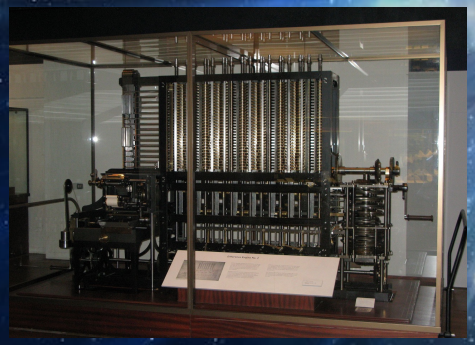
“If you wish to make an apple pie from scratch, you must first invent the universe.”



Carl Sagan
November 9, 1934 -- December 20, 1996



Alan Turing
1912 – 1954
Turing Machine (1936)



Babbage Difference Engine

Ada Lovelace
1815—1842
First Programmer

Alonzo Church
1903 – 1995
Lambda Calculus (1930s)

Tiny Computers, Tiny Languages

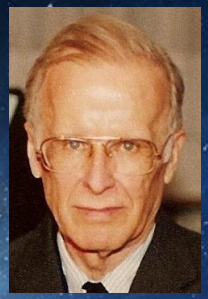
The ENIAC Computer
1945

First **programmable** digital computer

First program:
feasibility of nuclear weapons

AUTODOCDE

1952, Alick Glennie
First **compiled** programming language



FORTRAN
John Backus
1953

LISP
John McCarthy
1960

FLOW-MATIC/COBOL
Grace Hopper
1954

ALGOL

1958
Designed by committee

1950s: The Dawn of the Digital Era

Smalltalk

Object-oriented programming
Mid 1970s

C++

1980

Prolog

Logic programming
1972

C

1972







SQL

1978

ML

Statically typed functional language
1973

Growth of Digital Computers

Python
1990

Haskell
1990

Java
1995

Go
2009

Smalltalk

C++

Prolog

C

Julia
2012

ML

SQL

JavaScript
1995

TypeScript
2012

Rust
2015

Swift
2014

The Modern Era

Questions

Why are there so many programming languages?

Which language should I learn? Should I use?

Are some languages worse than others? Better?
How can I compare them?

What distinguishes one language from another?

Why are new languages being made today?

How are new languages made?

Why study programming languages?

- Be a *more effective programmer*
  - How to *choose languages* for your problems
  - How to *design and implement languages* when needed
- Become equipped to *learn new languages quickly*
- Be *prepared for an evolving world*
  - New languages are showing up all the time
- Enjoy an *aesthetic journey* through this elegant field (subjective)

What is a “programming language”?

“A programming language is a system of notation for writing computer programs.”

https://en.wikipedia.org/wiki/Programming_language
Accessed Friday, January 5

What is a “programming language”?

“Computer programming language, any of various languages for expressing a set of detailed instructions for a digital computer.”

https://www.britannica.com/technology/computer-programming-language
Accessed Friday, January 5

A programming language has two parts:

Syntax

What does a program look like?

Ancient Mesopotamia

Semantics

What does a program do?

"Your debt
is canceled"

A programming language has two parts:

Syntax

What does a program look like?

Python

```
x = 5
print(x)
```

Semantics

What does a program do?

- Create a variable called “x”
- Print the contents of that variable

A programming language has two parts:

Syntax

What does a program look like?

JavaScript

```
let x = 5;
console.log(x)
```

Semantics

What does a program do?

- Create a variable called “x”
- Print the contents of that variable

A programming language has two parts:

Syntax

What does a program look like?

OCaml

```
let x = 5 in
Format.printf “%s” x
```

Semantics

What does a program do?

- Create a variable called “x”
- Print the contents of that variable

This course is all about *precisely defining programming languages*

Syntax

What does a program look like?

Formal descriptions as grammars

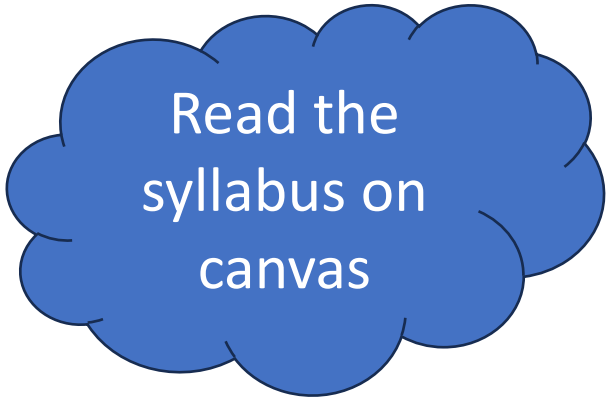
Semantics

What does a program do?

Programs that run programs

Interpreters!

- Grow big languages out of small ones
- Implement new languages



Course Logistics & Content

- Course resources, staff, and policies
- Course modules and overview
- Grading and evaluation

Course Staff

- Instructor: Steven Holtzen
  - Assistant Professor at Northeastern since 2021
  - This is my first time teaching this course

- Teaching Assistants

Minsung Cho
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You are at one of the best schools for PL in the world

https://prl.khoury.northeastern.edu/people.html

Many of the tools we use in this class were developed here!

Module 0: Plait

"Most programming languages — including the most widely used — have serious design defects, so that learning such languages is less a matter of mastering a style than of learning workarounds for the language designer's mistakes... I believe that the most reasonable approach to this problem is to first learn to program in a single well-designed programming language (or perhaps a small number of stylistically varied well-designed languages) that imposes a minimal number of obstacles to the programming task"

John C. Reynolds
1935 -- 2017

Some Thoughts on Teaching Programming and Programming Languages, 2012

Module 0: Plait Learning Objectives

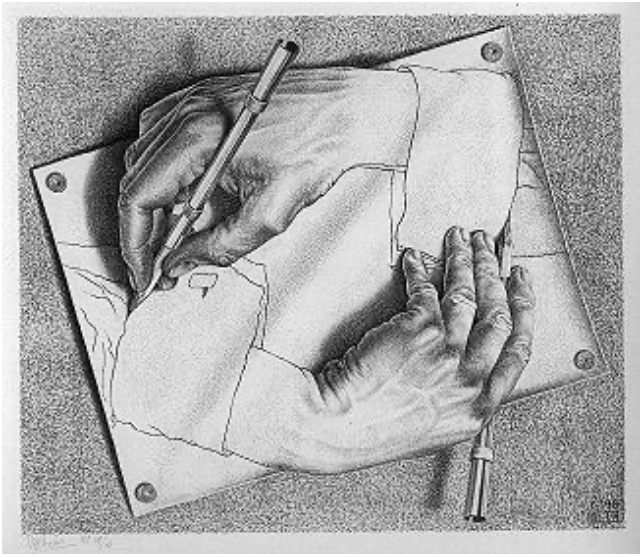
1. Become familiar with *functional programming* and how to solve problems in a *functional style*

2. Become familiar with a *typed language* and *programming with types*

3. Gain practice *learning a new language from scratch*

Module 1: Growing an interpreter

- We will grow the *syntax* and *semantics* of a tiny core language called SMoL (Standard Model of Languages)
  - We will *program interpreters* for this language in Plait
- Language features include:
  - Conditionals, scope and binding, first-class functions, macros, object, state

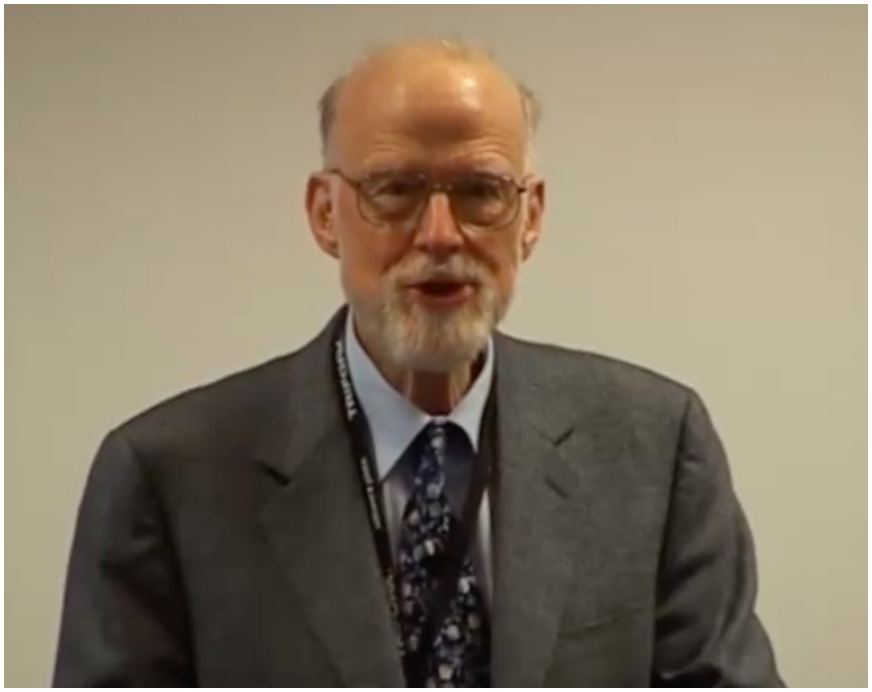


Drawing Hands
M. C. Escher 1968

Module 2: Types

- Types are form of ***checked specification*** for programs
- Example: Java

```
import java.util.Scanner;

public class HelloWorld {

    public static void main(String[] args) {

        // Creates a reader instance which takes
        // input from standard input - keyboard
        Scanner reader = new Scanner(System.in);
        System.out.print("Enter a number: ");

        // nextInt() reads the next integer from the keyboard
        int number = reader.nextInt();

        // println() prints the following line to the output
        System.out.println("You entered: " + number);
    }
}
```



Tony Hoare

Types can't prevent all bugs:
this is a valid Java program:

```
public class Example {

    public static void main(String[] args) {
        Object obj = null;
        obj.hashCode();
    }

}
```

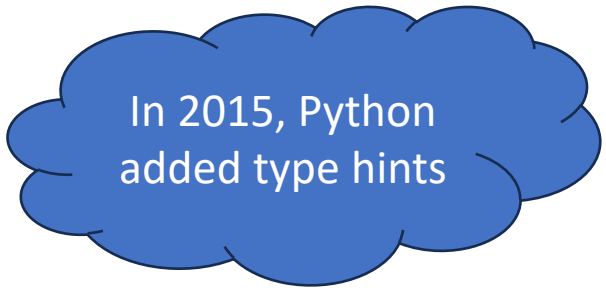
Recommended viewing:

https://www.infoq.com/presentations/Null-References-The-Billion-Dollar-Mistake-Tony-Hoare/

Module 2: Why study types?

- You ***will*** encounter types in your day-to-day programming

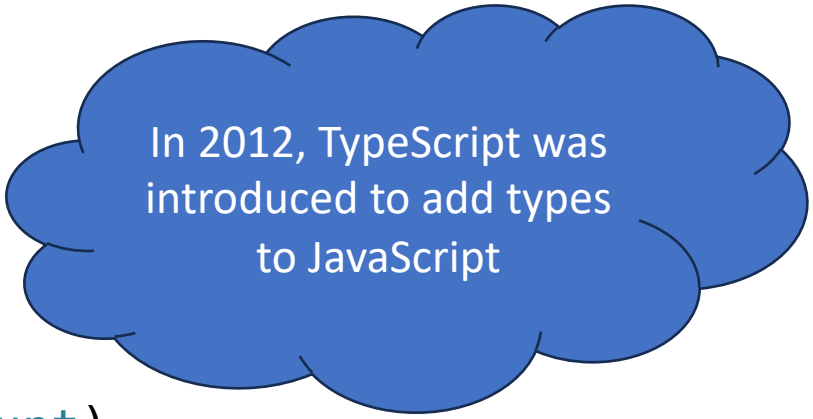
```
def greeting(name: str) -> str:
    return 'Hello ' + name
```



Module 2: Why study types?

- You ***will*** encounter types in your day-to-day programming

```
interface Account {
    id: number
    displayName: string
    version: 1
}

function welcome(user: Account)
{
    console.log(user.id)
}
```



Module 2: Types

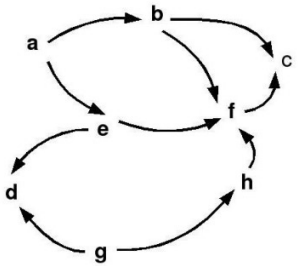
- We will build our own type system for SMoL
  - Learn the formal properties of type systems
- Study ***type inference*** and techniques to make programming with types easier
- Encounter the rich ***mathematical structure*** of types
  - What formal properties can a type system give you?

* Subject to change

Module 3: Beyond SMoL*

- We will study advanced languages and language features that go beyond SMoL
  - Implement and program some interesting languages

```
a(g,h).
a(g,d).
a(e,d).
a(h,f).
a(e,f).
a(a,e).
a(a,b).
a(b,f).
a(b,c).
a(f,c).
```



Logic programming

Laziness

Goal: Broaden your horizons on what programming languages can look like

Schedule overview

- Available here:
  https://docs.google.com/spreadsheets/d/e/2PACX-1vQNTDbNs-WnG7YU5iebhT9XuWfTNF2LBSPWzU1ctif8YrNuciQWZDtzU2hviaFt22asf1C2O27tdOoe/pubhtml?gid=0&single=true

CS4400 Spring'24 Schedule : Sheet1

Module	Date	Lecture title	Topics	Resources
Introduction to Plait and Functional Programming	Monday Jan 8	Introduction and course overview	- Why programming languages? - A first look at Racket/Plait	https://docs.racket-lang.org/plait/Tutorial.html Sections 1.1 -- 1.5
	Wednesday Jan 10	Programming in Racket and Plait	- Solving problems functionally and recursively - How to write tests in Plait - How Plait's type system works	https://docs.racket-lang.org/plait/Tutorial.html Sections 1.1 -- 1.8
	Monday Jan 15	**No Class --- Martin Luther King Jr. Day**		
	Wednesday Jan 17	**No Class --- Steven Traveling for POPL**	- Optional in-class workshop on Plait	
Building a SMoL Interpreter	Monday Jan 22	Abstract Syntax	- Abstract syntax trees - A simple calculator language - Interpreting a language by hand	PLAI pg. 17 -- 27 See https://www.plai.org/3/2/PLAI%20Version%203.2.2%20printing.pdf
	Wednesday Jan 24	Evaluation	- Implementing and testing the evaluator - Parsing and s-expressions	PLAI pg. 28 -- 37
	Monday Jan 29	Conditionals	- Extending the syntax with `if` - Design space of `if` - Adding Booleans, the `Value` type	PLAI pg. 37 -- 47
	Wednesday Jan 31	Local binding	- The `let` syntax - Scope - An evaluator for `let`	PLAI pg. 47 -- 57
	Monday Feb 5	First-class functions	- Syntax for functions - Adding functions to the `Value` type - Evaluating functions	PLAI pg. 58 -- 69
	Wednesday Feb 7	Growing SMoL: Macros	- Desugaring - An example: Strict If - define-syntax - Macro stepping in DrRacket	PLAI pg. 71 -- 84
	Monday Feb 12	Objects I	- The "standard model" of objects - State - Access control	PLAI pg. 85 -- 95

Schedule overview

Types	Wednesday Feb 14	Objects II	- Extending objects: mixins, traits	PLAI pg. 97 -- 106
	Monday Feb 19	Introduction to types	- What are types? - A simple type checker - How to read and write typing judgments	PLAI pg. 109 -- 122
	Wednesday Feb 21	Typing functions	- The typing rule for functions - Assume-guarantee reasoning - Making a typechecker - Handling recursion	PLAI pg. 123 -- 132
	Monday Feb 26	The Simply Typed Lambda Calculus	- Syntax and a type checker - The Omega term and normalization	
	Wednesday Feb 28	Safety and soundness	- What is type safety, why do you want it - Enforcing type safety - Type safety for simply-typed lambda calculus	PLAI pg. 133 -- 144
	Monday Mar 4	**No Class -- Spring Break**		
	Wednesday Mar 6	**No Class -- Spring Break**		
	Monday Mar 11	Type inference	- Basic goals of type inference - Hindley-Milner - Complexity of type inference	PLAI pg. 145 -- 149
	Wednesday Mar 13	Algebraic datatypes and pairs	- Typechecking algebraic datatypes and pairs - Proofs and programs: Curry-Howard	PLAI pg. 150 -- 153
	Monday Mar 18	Subtyping	- Adding subtyping to typing judgments - Applications: information flow analysis	PLAI pg. 165 -- 170
	Wednesday Mar 20	Gradual typing	- TypeScript, typed Python, Typed Racket	PLAI pg. 170 -- 176
Paradigms	Monday Mar 25	Logic Programming I	- Programming with relations - Unification - A simple type checker	PLAI pg. 178 -- 184
	Wednesday Mar 27	Logic Programming II		PLAI pg. 193 -- 202
	Monday Apr 1	Laziness I	- Evaluation schemes: eager, lazy, call-by-need, call by name - Consequences of evaluation schemes - A lazy evaluator - Programming in lazy languages	
	Wednesday Apr 3	Laziness II	- Modeling state and mutation - A taste of Haskell	
	Monday Apr 8	Effects I	- Effects in Racket - Effect handlers	
	Wednesday Apr 10	Effects II		
	Monday Apr 15	**No Class -- Patriot's day**		
	Wednesday Apr 17	Slack day		

Textbook

- *Programming Languages: Application and Interpretation*, Third Edition, by Shriram Krishnamurthy

- Open-access textbook, available at: https://www.plai.org/

- We will follow it closely: you are encouraged to read the textbook sections ahead or after lecture as a reference

Prerequisites

- Required: CS3500 (Object oriented design) or Equivalent

- Highly recommended:

  - Experience programming in at least one major programming language

  - This will be a programming-intensive course

Input/Output

- Important course announcements will be broadcast as Canvas Announcements
  - You should check to make sure that you receive these
- We will use Piazza
  - Please ask all course questions there
  - You can ask private questions
  - You should have received an email invitation
- Notes/slides will be posted on Canvas after lecture

Assignments and grading

Type	Frequency	Percent of Final Grade
Homework	About once a week	60%
Quizzes	About 4	40%

Range	> 93	[90,93)	[87, 90)	[83, 87)	[80, 83)	[77, 80)	[73, 77)	[70, 73)	[67, 70)	[60, 67)	<50
Grade	A	A-	B+	B	B-	C+	C	C-	D+	D	F

Note: Some assignments / problems will be marked as “CS5400”. These are only for students enrolled in CS5400.

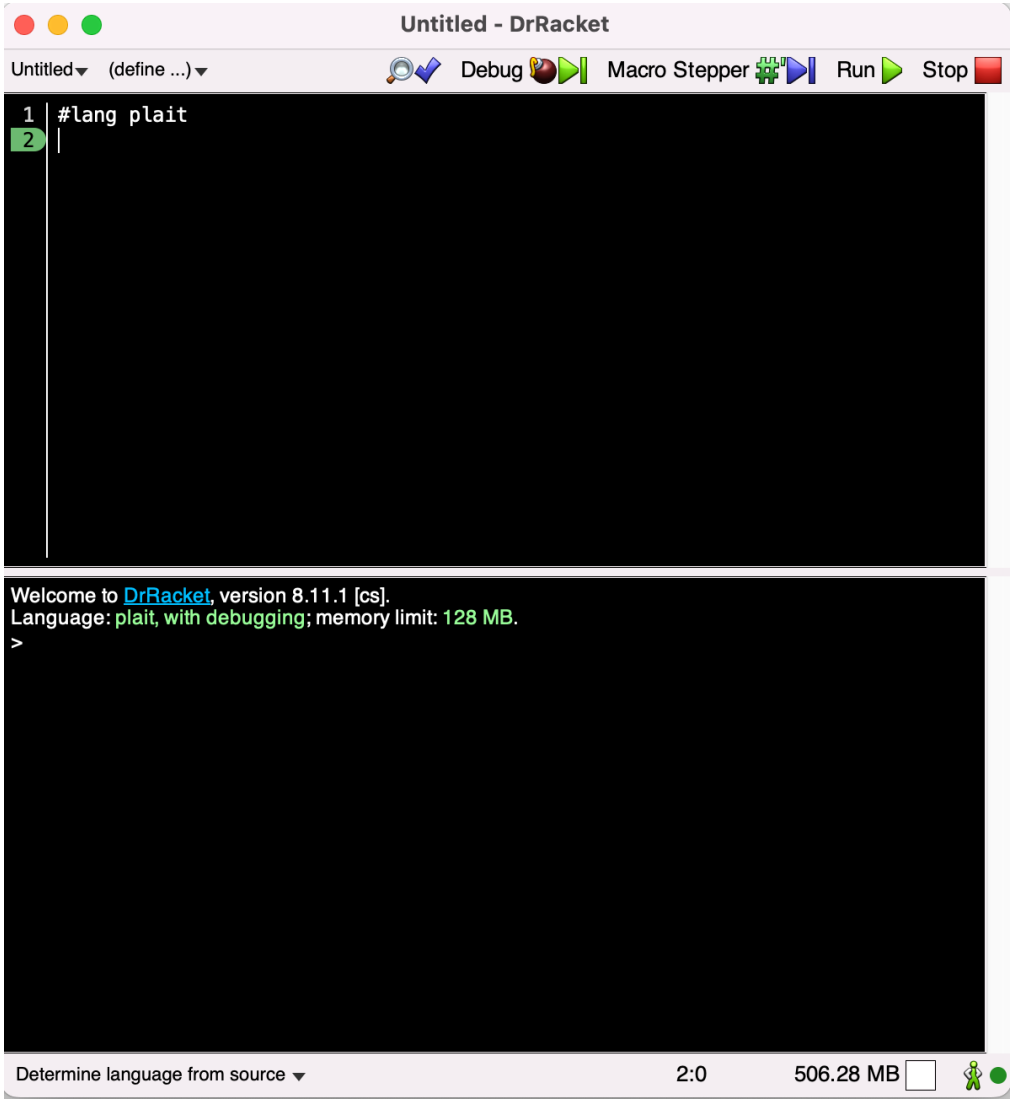
A taste of Plait

Goals:

- Set up and install Plait
- Understand how to write small Plait programs and call functions
- Know the key properties of Plait

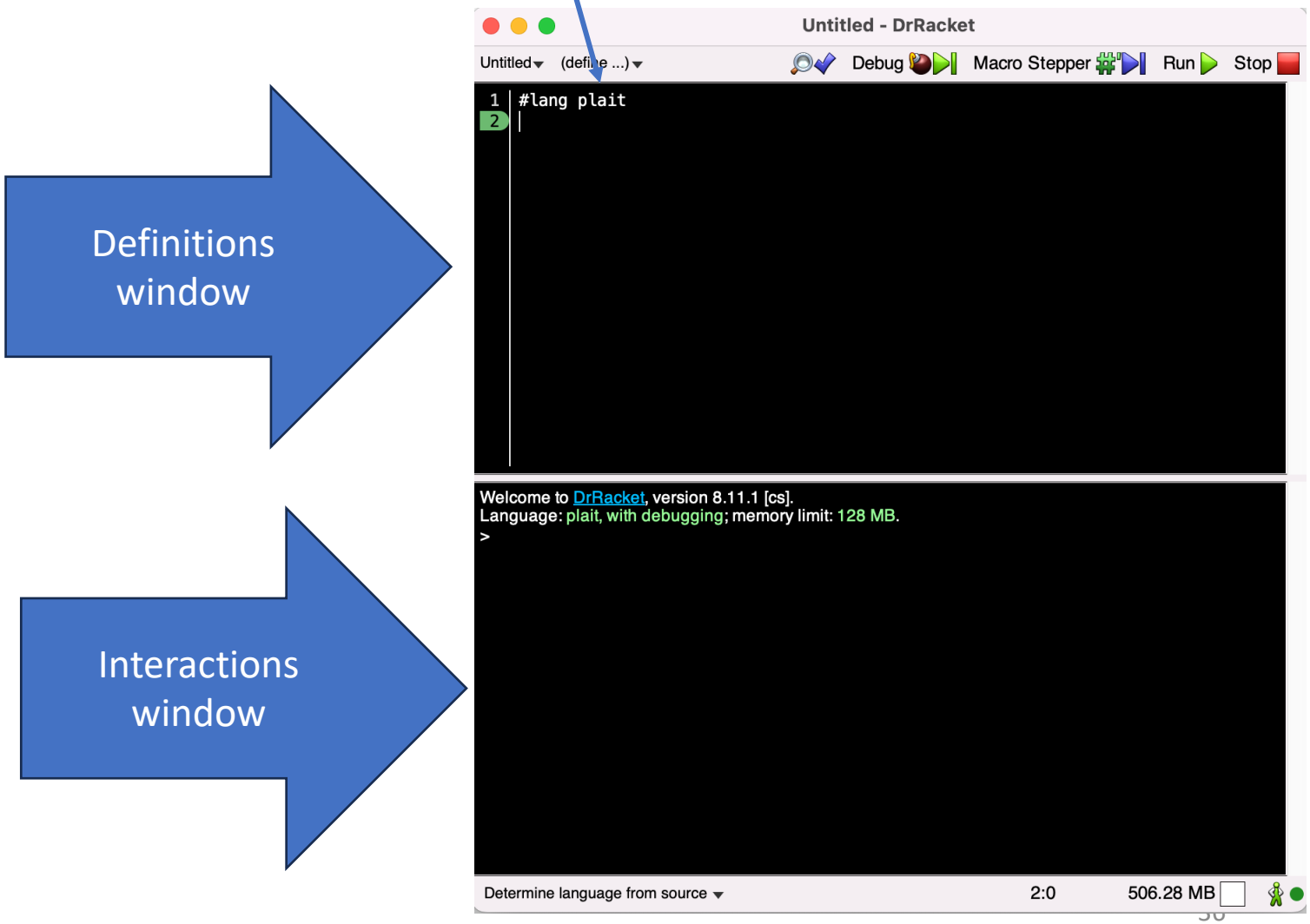
Setting up Plait

- Follow https://docs.racket-lang.org/plait/getting-started.html
- Download DrRacket (use version 8.11.1)
- You will need to install the Plait .plt file



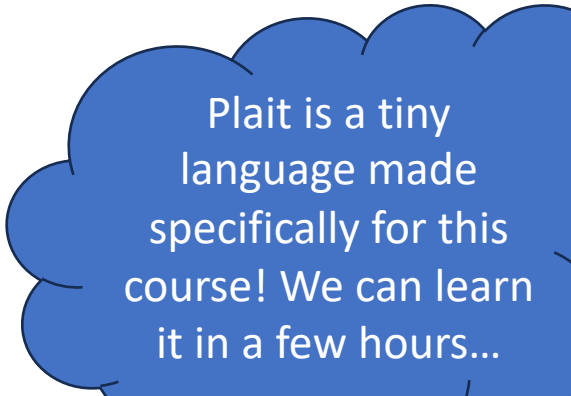
DrRacket

Tells DrRacket which programming language to use



Plait Resources

- Plait website: https://docs.racket-lang.org/plait/
- Plait tutorial: https://docs.racket-lang.org/plait/Tutorial.html
- YouTube video tutorial: https://www.youtube.com/playlist?list=PLbdXd8eufjyUT8rza1qDcS0RUnRTr9A1f
- Plait CheatSheet on Canvas
- Ask on Piazza if you get stuck :)



Simple data

- Enter code into the Interaction window and press “enter” to run your code
- Basic data types:
  - Numbers `1, 1.2, 1/3`
  - Strings “`quoted`”
  - Symbols `‘a, ‘b, ‘sym, …`
  - Booleans `#t #f`
- Comments begin with `;`

Input Plait program called a **term** or **expression**

Type of entered term; every term has a type

Value program evaluates to

An unusual type; we will see more of it later

```
> 4
- Number
4
> "hello"
- String
"hello"
> 'a
- Symbol
'a
> #t
- Boolean
#t
> #f
- Boolean
#f
```

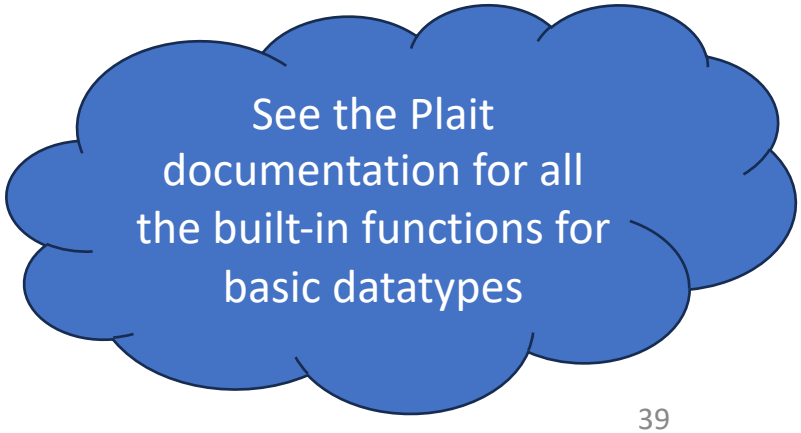
Calling functions

- Adding two numbers:
  - Unusual syntax! We will come to appreciate it.

```
> (+ 1 2)
- Number
3
```

- Some built-in functions for integers:

```
> (max 1 2)
- Number
2

> (- 2 3)
- Number
-1

> (< 10 20)
- Boolean
#t
```



Calling functions

- Chaining together functions:

```
> (+ 1 (max 3 4))
– Number
5
```

- A note on floating point:

```
> (eq? (/ 1.0 3.0) 1/3)
– Boolean
#f
```

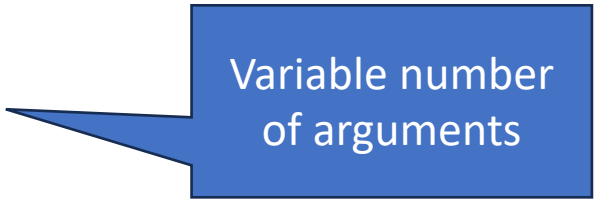
- Be careful! Plait represents these two values differently

```
> 1/3
– Number
1/3
```

```
> (/ 1.0 3.0)
– Number
0.3333333333333333
```

Some functions on Booleans

```
> (and #t #f)
- Boolean
#f

> (and #t #t #f)
- Boolean
#f

> (or #f #t)
- Boolean
#t

> (not #t)
- Boolean
#f

> (eq? #t #f)
- Boolean
#f
```



Some functions on Strings

```
> (equal? "hello" "world")
- Boolean
#f

> (string-append "hello"
"world")
- String
"helloworld”

> (substring "hello" 1 3)
- String
"el"
>
```

Get substring between index 1 and 3, inclusive lower-bound, exclusive upper-bound

Types

- Plait functions expect their arguments to have certain types

Type signature says the max function takes two Number as input and returns a Number

```
> max
- (Number Number -> Number)
#<procedure:max>
```

- If you call a function with the wrong type of arguments, Plait will help you by complaining

```
> (max 1 "oops")
typecheck failed: Number vs. String in:
max
"oops"
```

`if` expressions

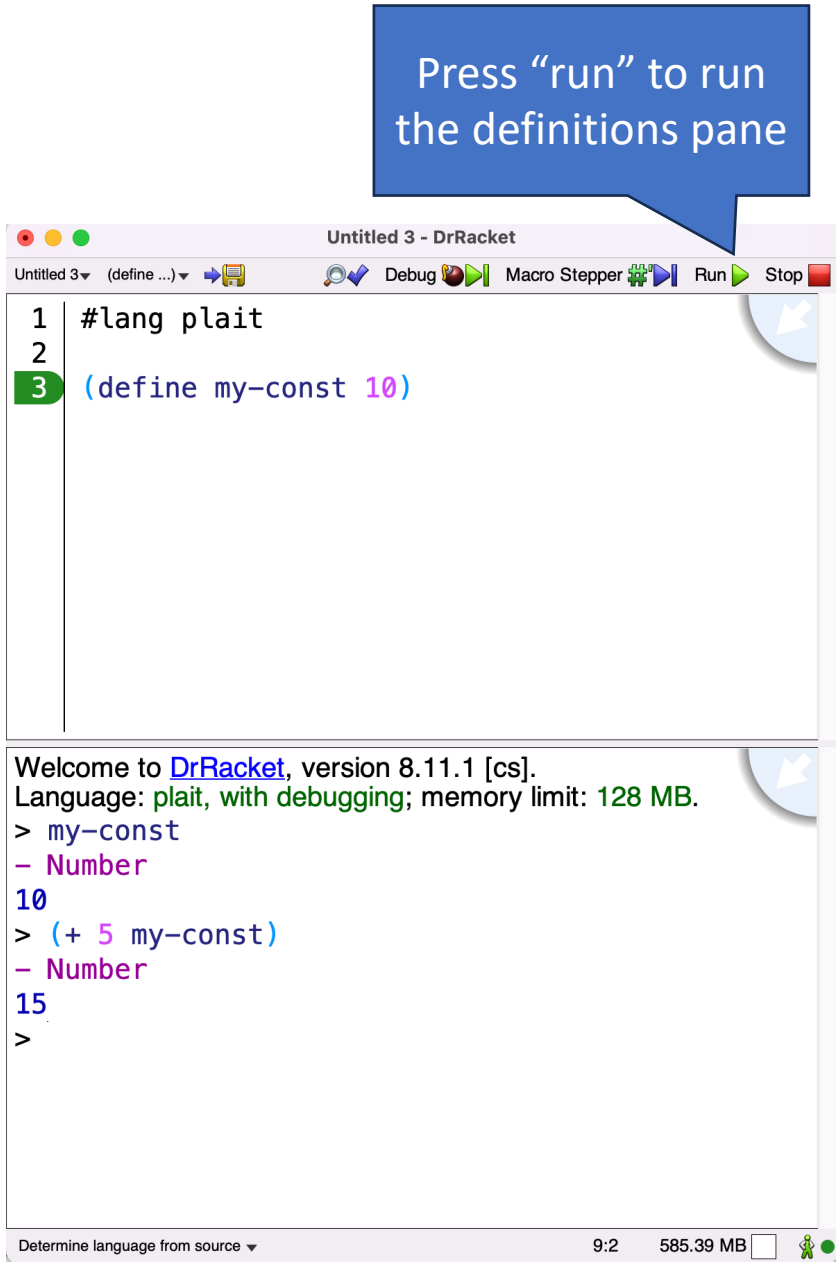
`(if guard thn els)`
If the guard is true, evaluate thn; otherwise, evaluate els

```
> (if #t "woohoo" "ohno")
- String
"woohoo"

> (if #t "what" 10)
typecheck failed: String vs. Number in:
  "what"
  10

> (if (< 10 20) 'ok 'oops)
- Symbol
'ok
```

`if` requires that both `thn` and `els` terms be the same type

Definitions

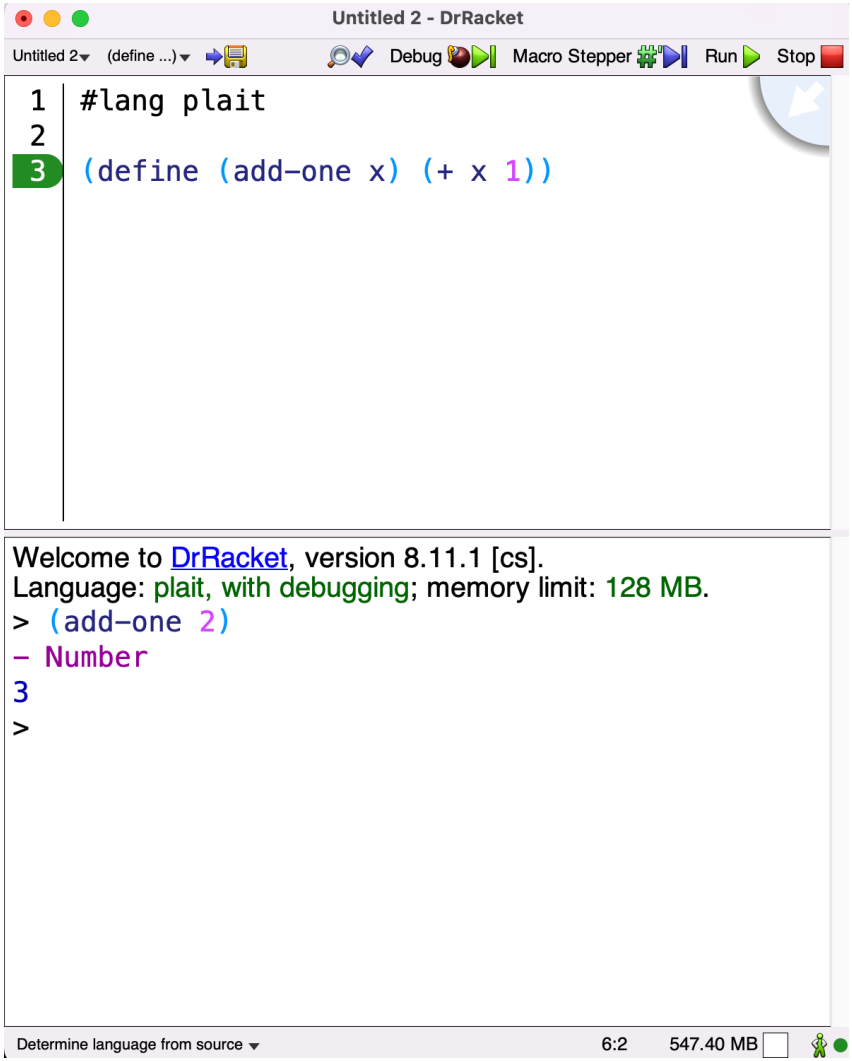
- Syntax:
  `(define id e)`
- `id` is an identifier, `e` is a Plait expression
- Creates a globally accessible constant called `id`



Defining functions

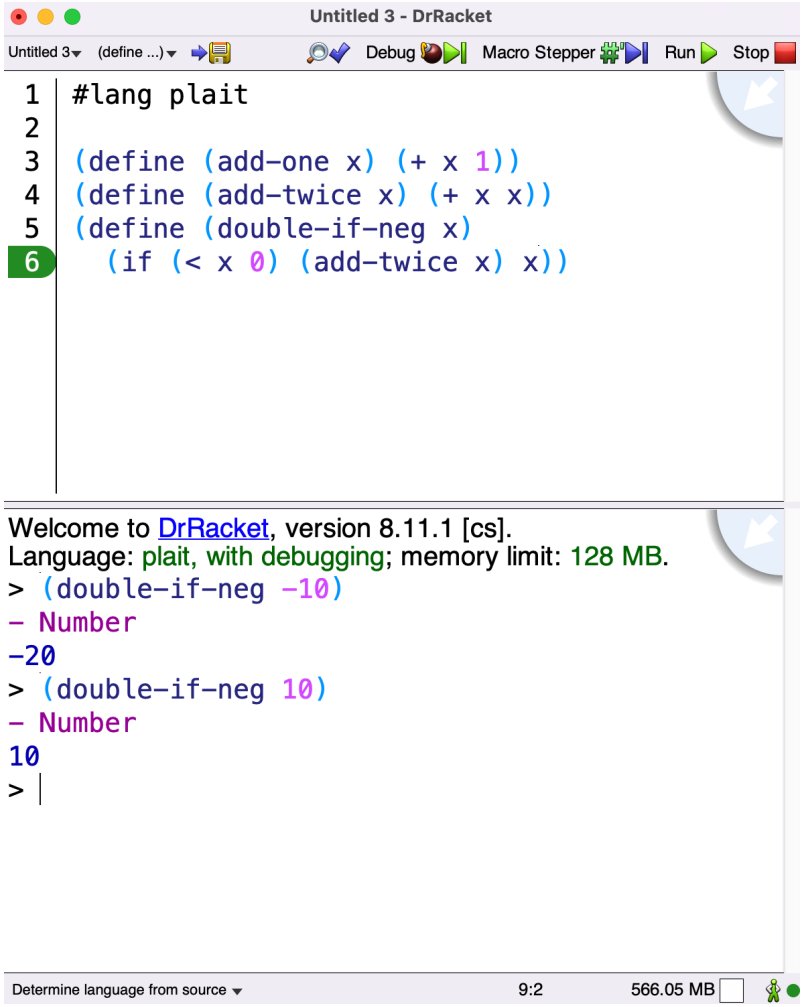
- Syntax:
  `(define (id arg1 arg2 …) e)`

- Creates a globally accessible function called `id` with arguments `arg1, arg2, …` and body `e`



Defining functions

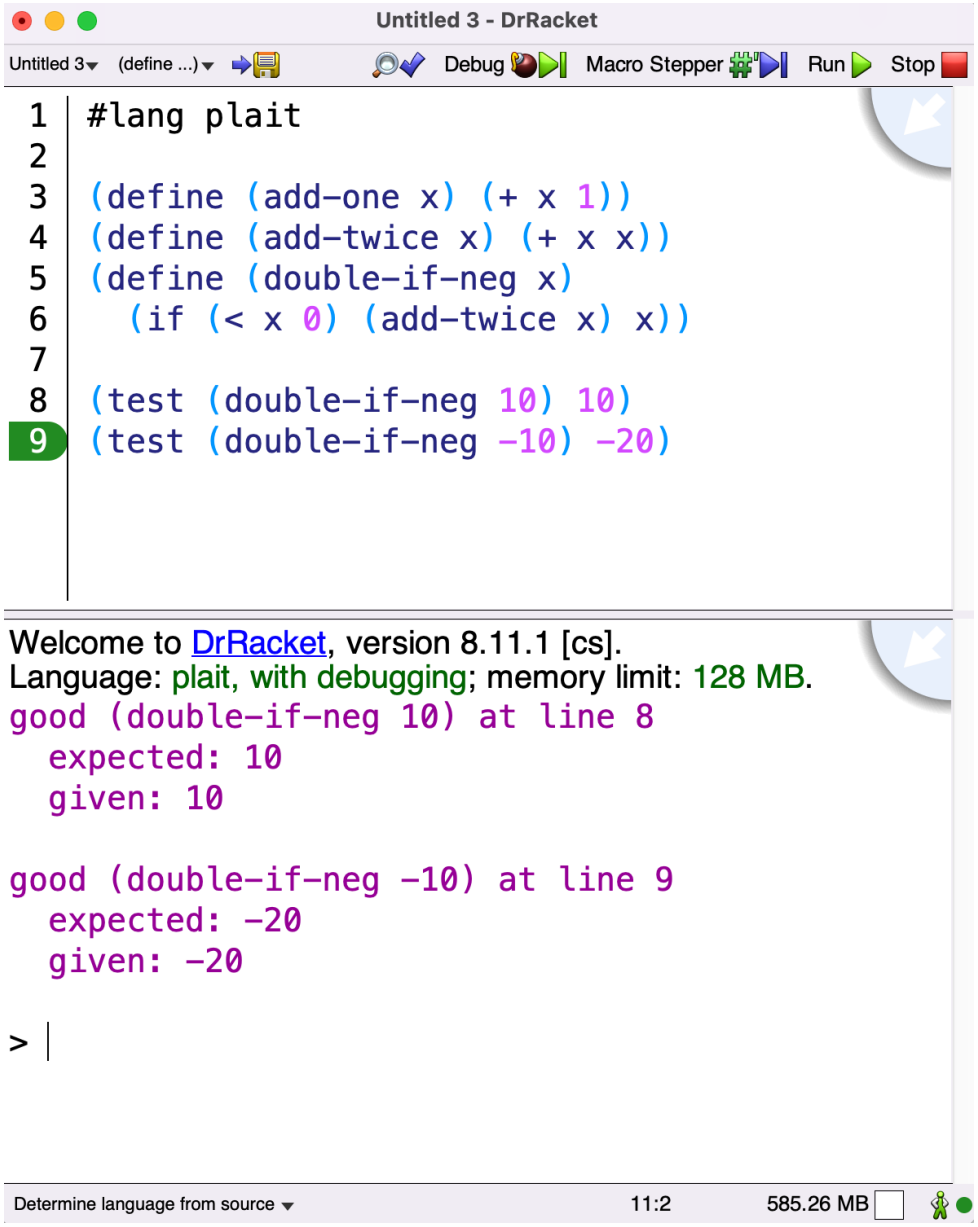
- Write a function “double-if-neg” that takes a number as an argument, and returns double that number if it is negative, otherwise return the input number



Testing

`(test e1 e2)`

tests that e1 and e2 evaluate to the same value



Conclusion

- Homework is due this Friday (Jan 12)

- Before next lecture:
  - Download DrRacket and install Plait
  - Try the first 2 homework problems

- Next time:
  - Bring a computer that is setup with Plait ready to do some in-class activities
  - We will see more Plait and practice solving more interesting problems