Machine Programming

Lecture 1 – Overview and Introduction to Synthesis

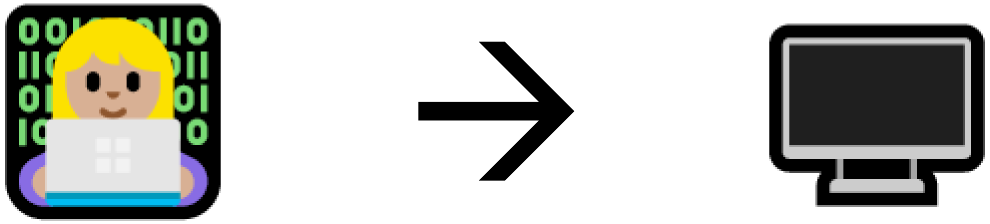
Ziyang Li

Instructor

Ziyang Li

- Assistant professor @JHU CS, 2025-
- Before that: PhD at University of Pennsylvania
- Research areas: Programming Language + Machine Learning
- Favorite PL: Rust & JavaScript

Programming...



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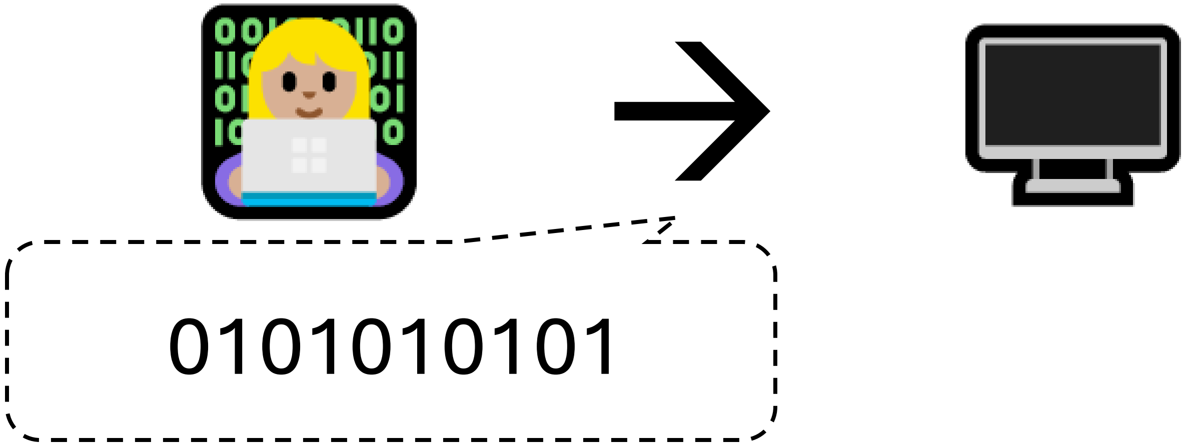
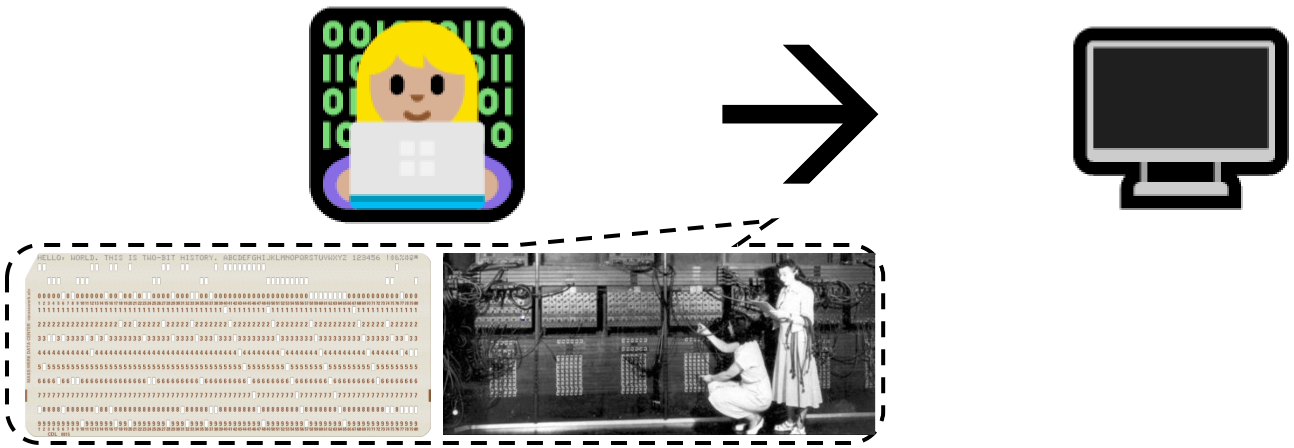
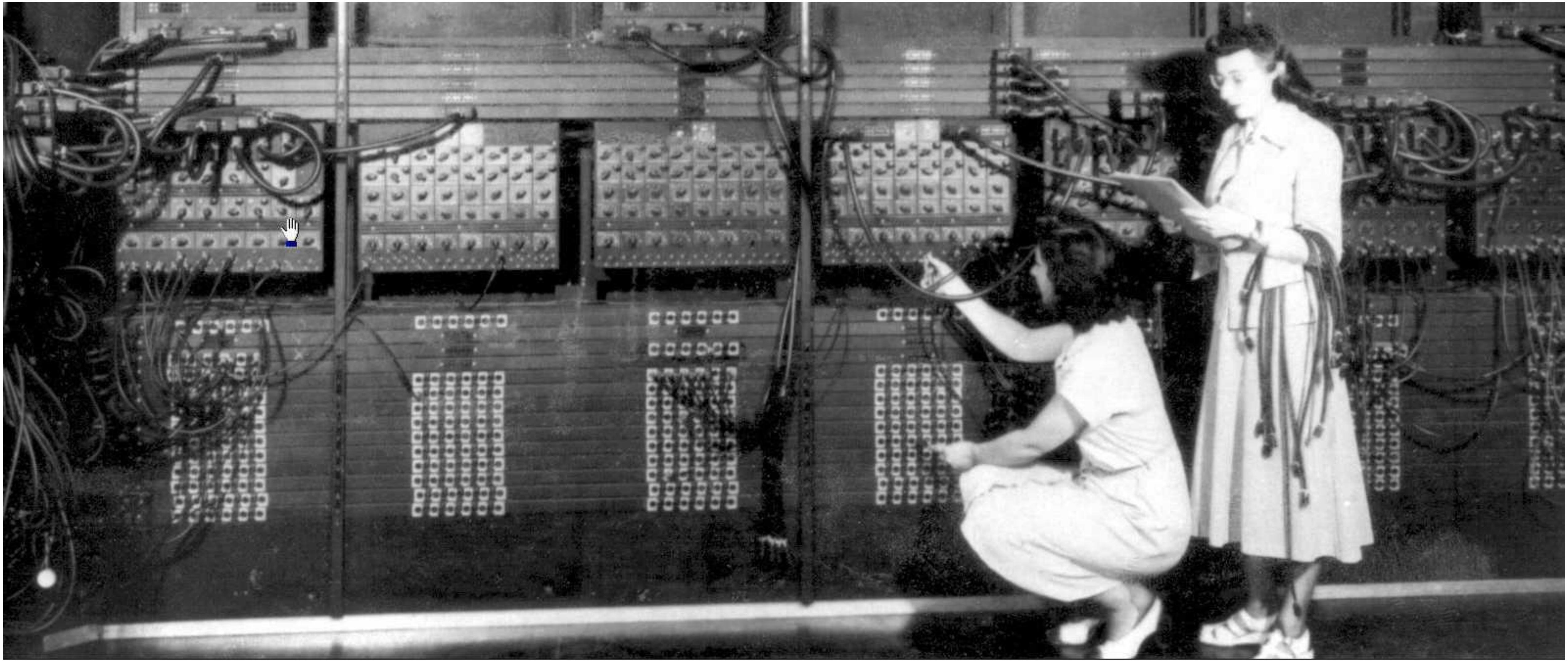


1940s–1950s: Binary

Programming...

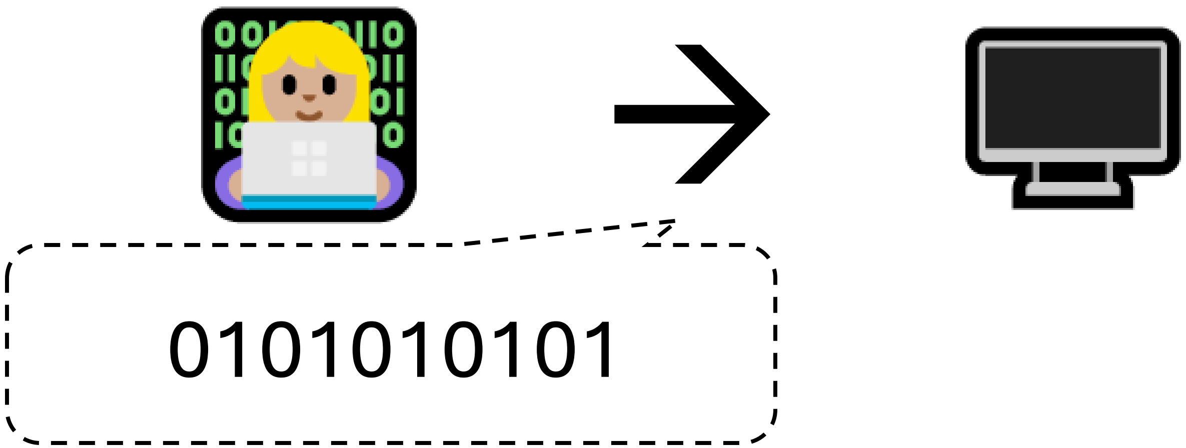


1940s–1950s




HELLO, WORLD. THIS IS TWO-BIT HISTORY. ABCDEFGHIJKLMNOPQRSTUVWXYZ 123456 !$&%#@*
MASS:WERK DATA CENTER <masswerk.at>
CDL 0815

Programming...



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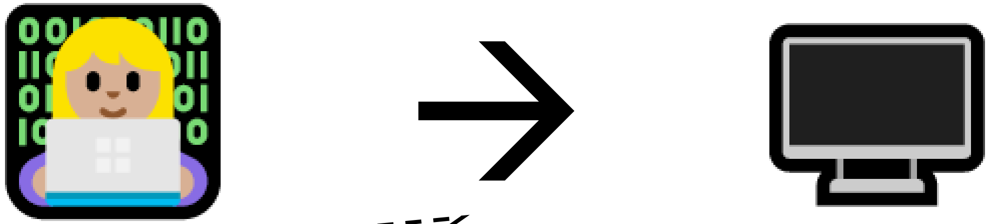
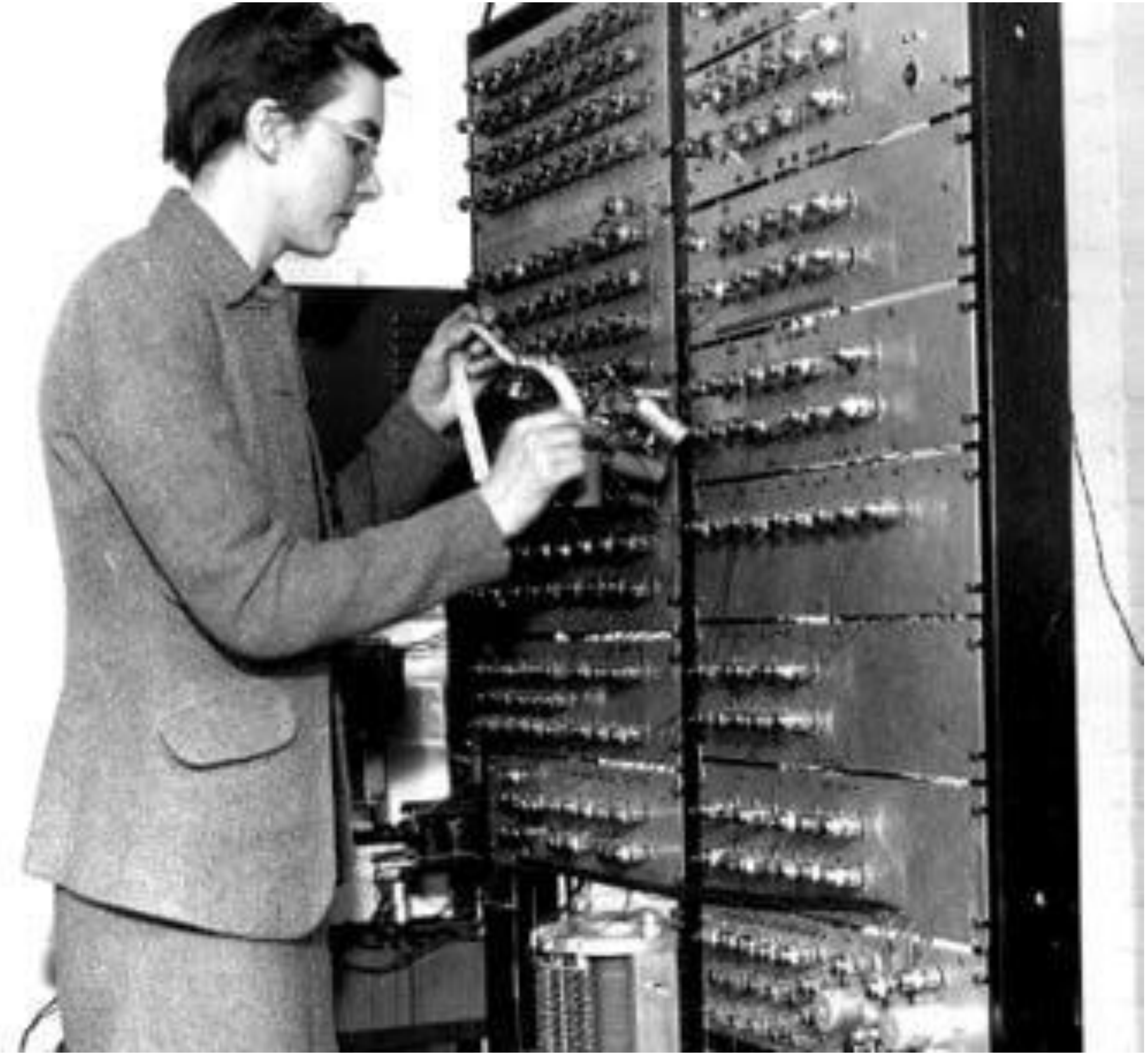
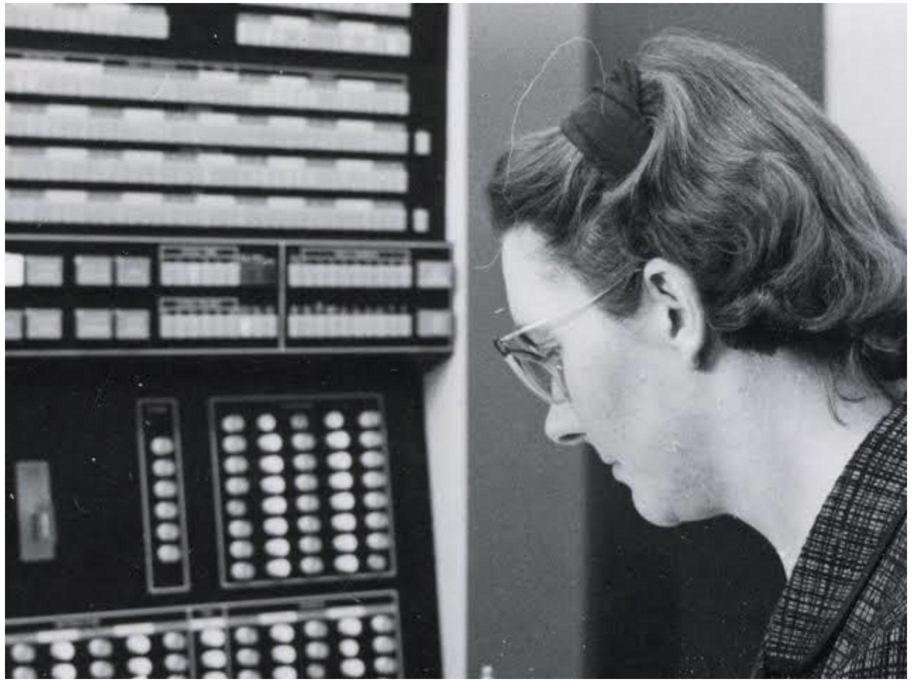


ADD R1, R2

1950s–1960s: Assembly

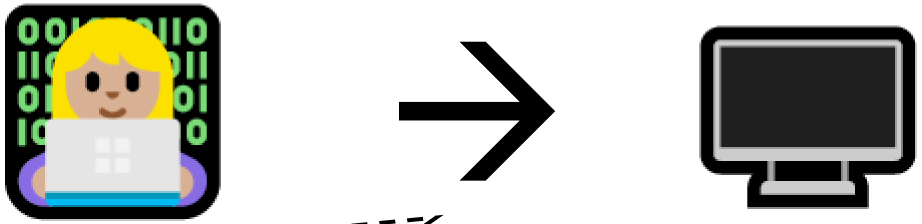




Kathleen Booth

1922–2022

Programming…



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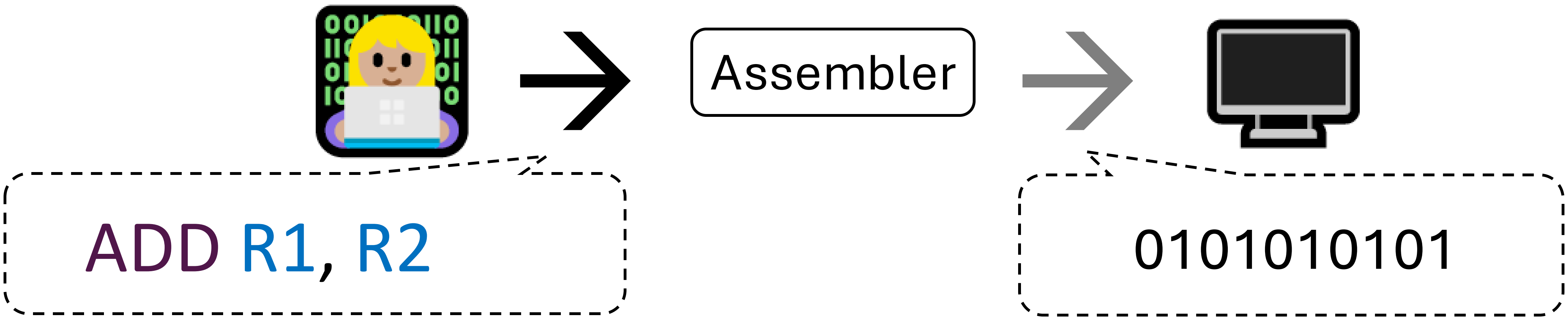
1950s–1960s: Assembly

Programming...



1950s–1960s: Assembly

The FORTRAN Automatic Coding System

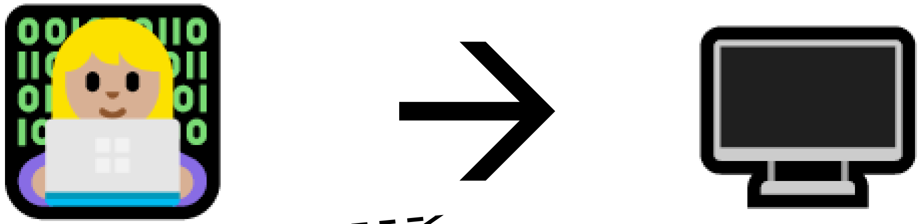
J. W. BACKUS†, R. J. BEEBER†, S. BEST‡, R. GOLDBERG†, L. M. HAIBT†,
H. L. HERRICK†, R. A. NELSON†, D. SAYRE†, P. B. SHERIDAN†,
H. STERN†, I. ZILLER†, R. A. HUGHES§, AND R. NUTT‖

INTRODUCTION

THE FORTRAN project was begun in the summer of 1954. Its purpose was to reduce by a large factor the task of preparing scientific problems for IBM's next large computer, the 704. If it were possible for the 704 to code problems for itself and produce as

system is now complete. It has two components: the FORTRAN language, in which programs are written, and the translator or executive routine for the 704 which effects the translation of FORTRAN language programs into 704 programs. Descriptions of the FORTRAN language and the translator form the principal

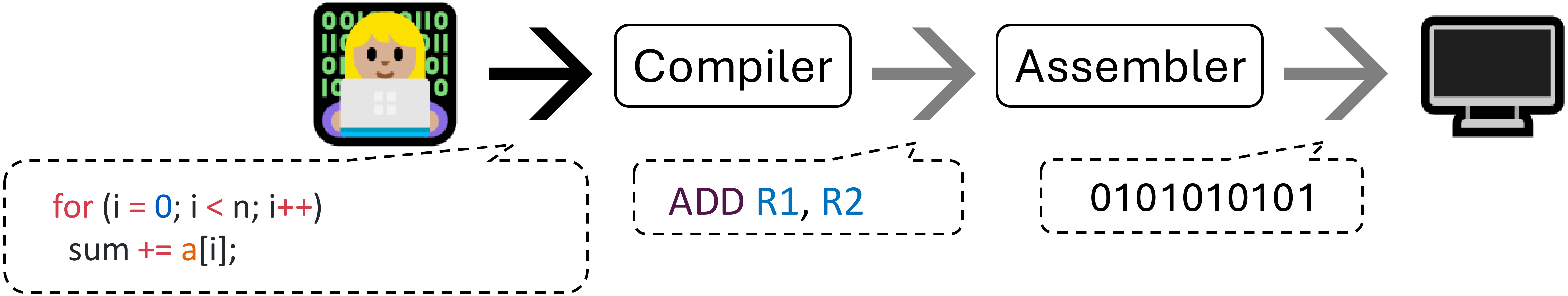
Programming...



```
for (i = 0; i < n; i++)
  sum += a[i];
```

1970s: High-level Language

Programming...



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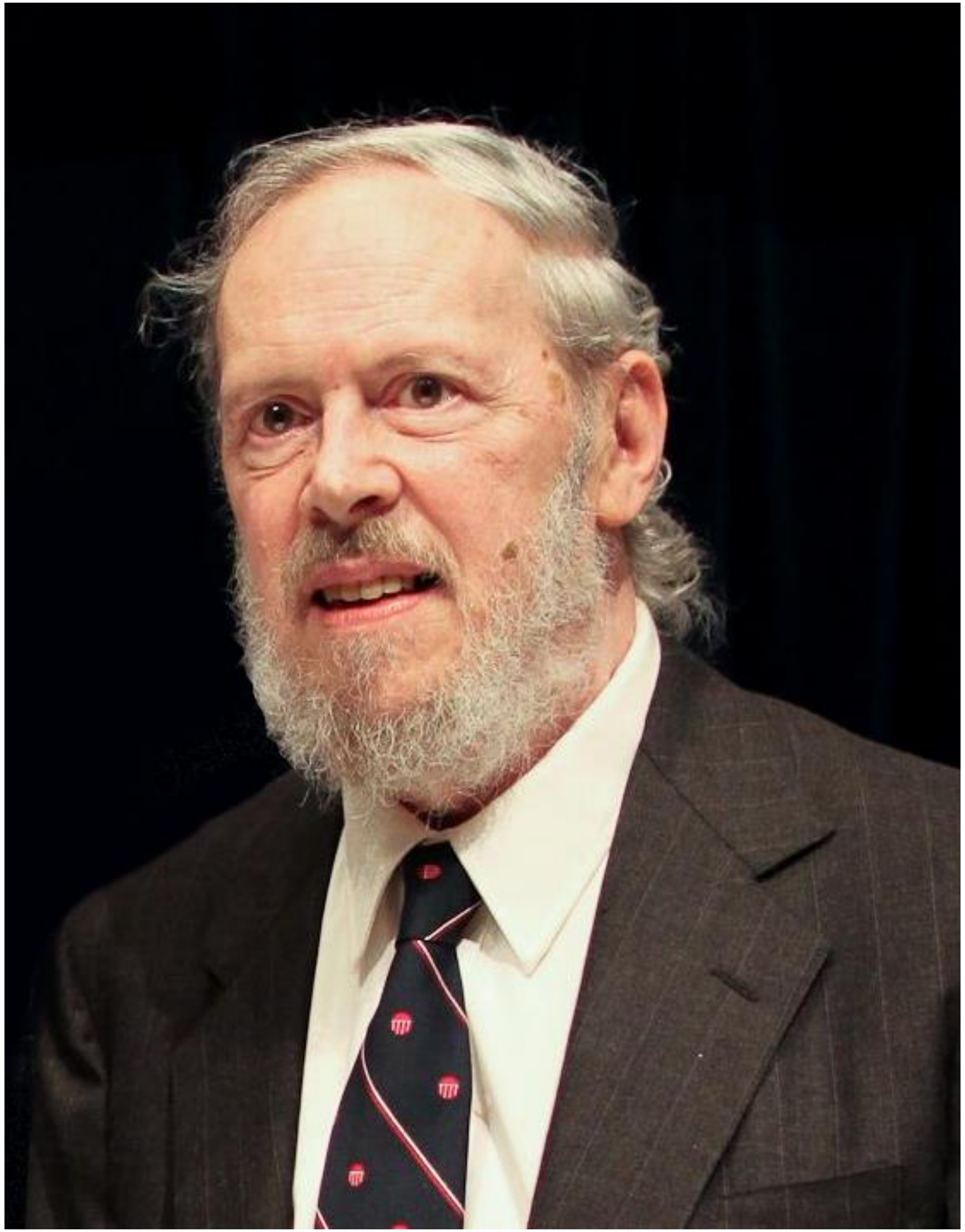
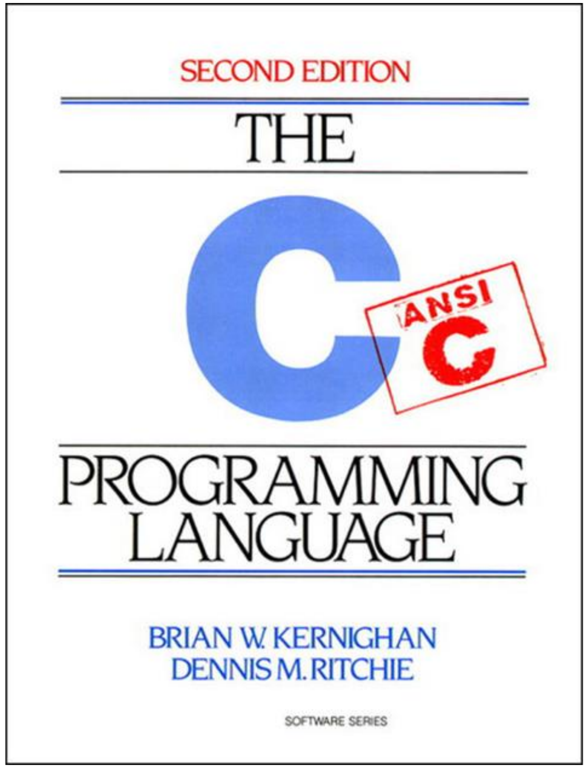


Dennis M. Ritchie

1941–2011



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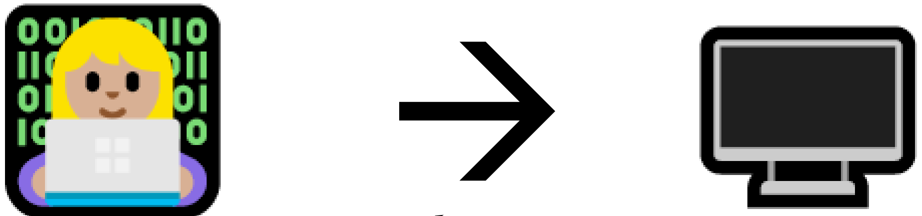

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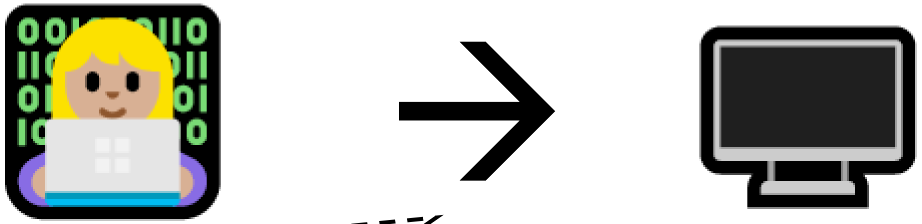

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for i in range(n):
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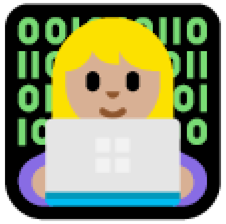
```

1980s onwards: Modern High-Level Languages

Programming…



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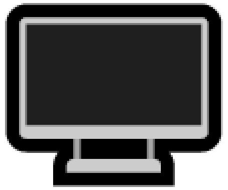

python™

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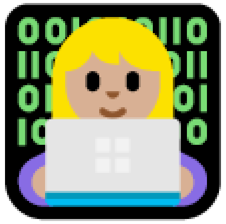

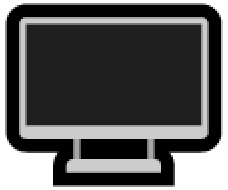

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for i in range(n):
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```javascript
for (var e of a) {
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```
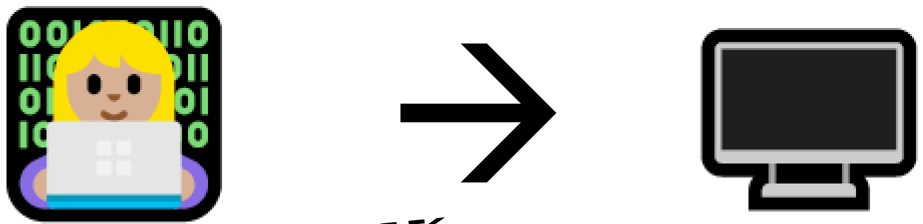

Programming...



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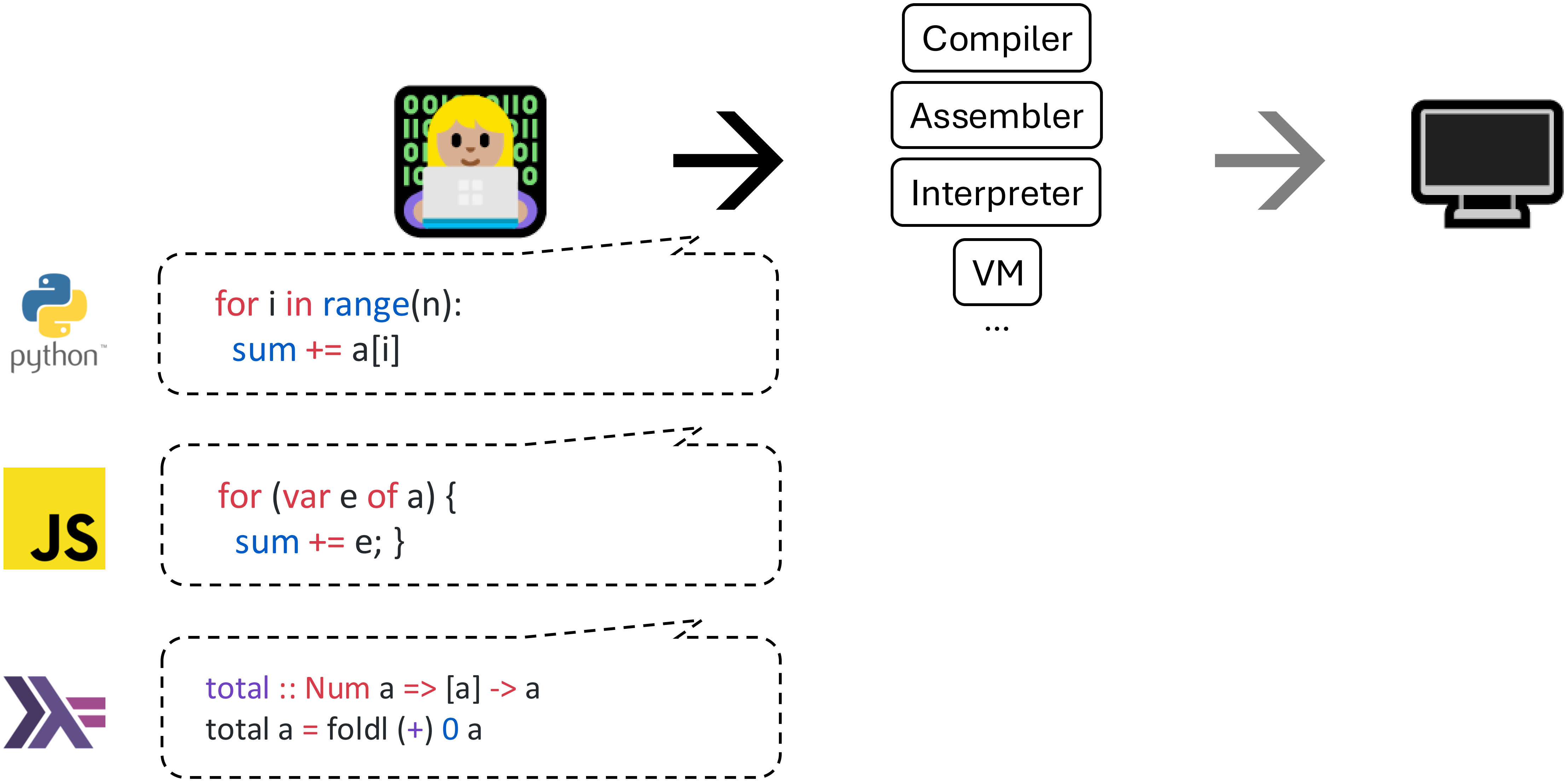
```haskell
total :: Num a => [a] -> a
total a = foldl (+) 0 a
```


Compiler
Assembler
Interpreter
VM
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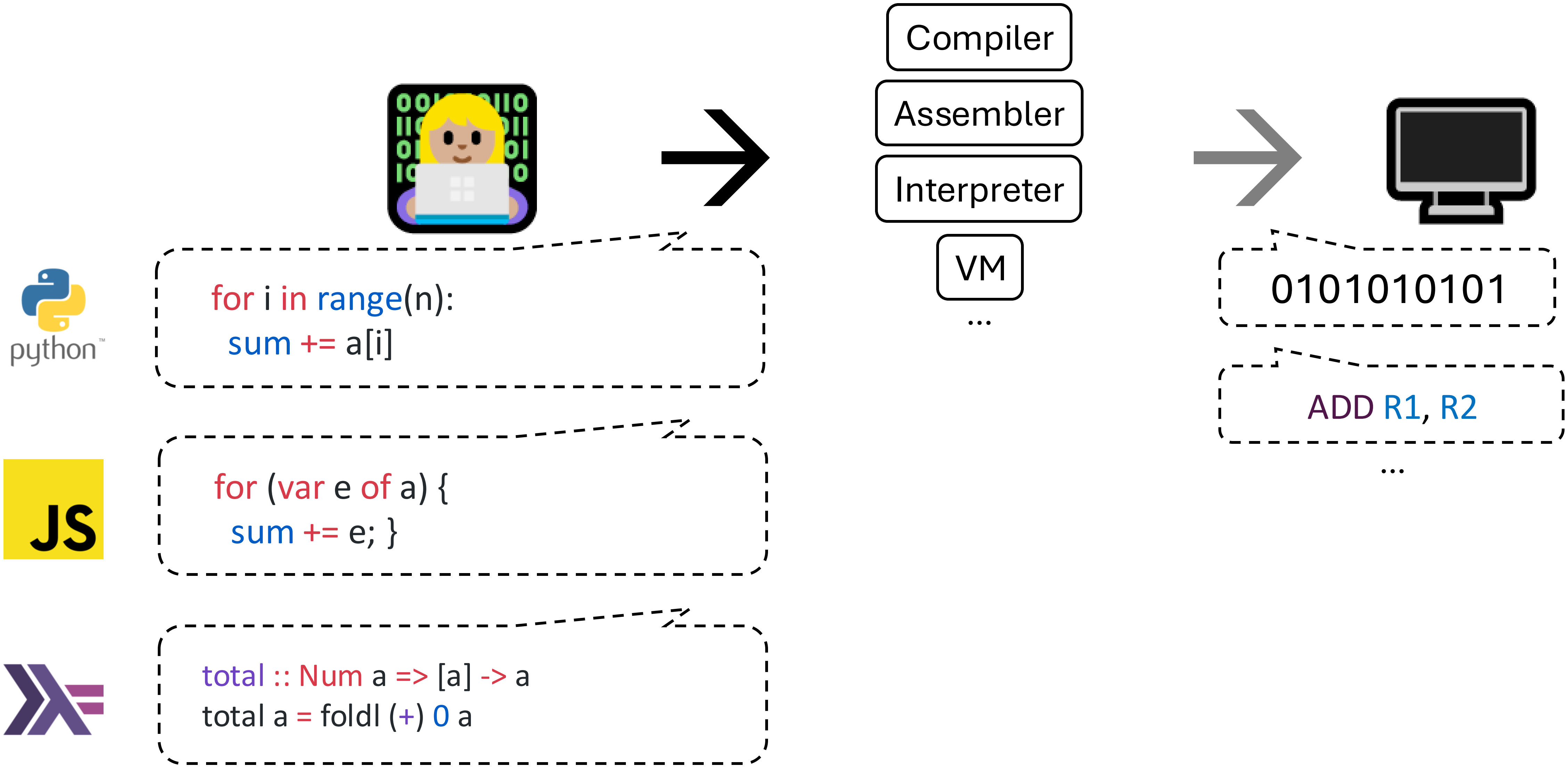

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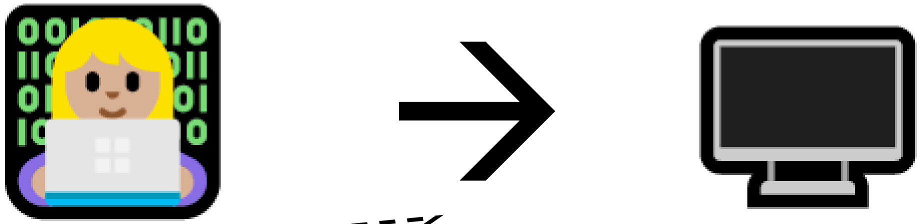
0101010101
ADD R1, R2
...

Programming...



```
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  sum += a[i]
```

Assembly

```
append:
 push ebp
 mov ebp, esp
 push eax
 push ebx
 push len
 call malloc
 mov ebx, [ebp + 12]
 mov [eax + info], ebx
 mov dword [eax + next], 0
 mov ebx, [ebp + 8]
 cmp dword [ebx], 0
 je null_pointer
 mov ebx, [ebx]

next_element:
 cmp dword [ebx + next], 0
 je found_last
 mov ebx, [ebx + next]
 jmp next_element

found_last:
 push eax
 push addMes
 call puts
 add esp, 4
 pop eax
 mov [ebx + next], eax

go_out:
 pop ebx
 pop eax
 mov esp, ebp
 pop ebp
 ret 8

null_pointer:
 push eax
 push nullMes
 call puts
 add esp, 4
 pop eax
 mov [ebx], eax
 jmp go_out
```

C

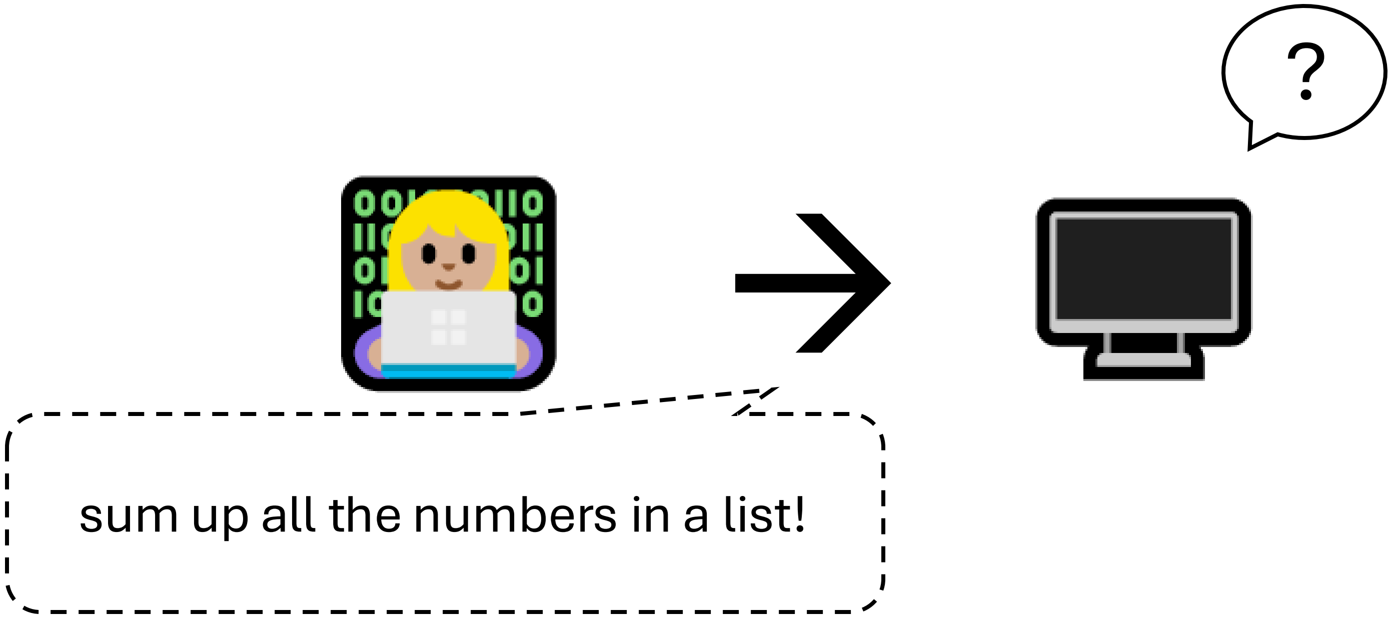
```c
void insert(node *xs, int x) {
  node *new;
  node *temp;
  node *prev;
  new = (node *)malloc(sizeof(node));
  if(new == NULL) {
    printf("Insufficient memory.");
    return;
  }
  new->val = x;
  new->next = NULL;
  if (xs == NULL) {
    xs = new;
  } else if(x < xs->val) {
    new->next = xs;
    xs = new;
  } else {
    prev = xs;
    temp = xs->next;
    while(temp != NULL && x > temp->val) {
      prev = temp;
      temp = temp->next;
    }
    if(temp == NULL) {
      prev->next = new;
    } else {
      new->next = temp;
      prev->next = new;
    }
  }
}
```

Haskell

```haskell
insert x [] = [x]
insert x (y:ys)
  | x ≤ y = x:y:ys
  | otherwise = y:(insert x ys)
```

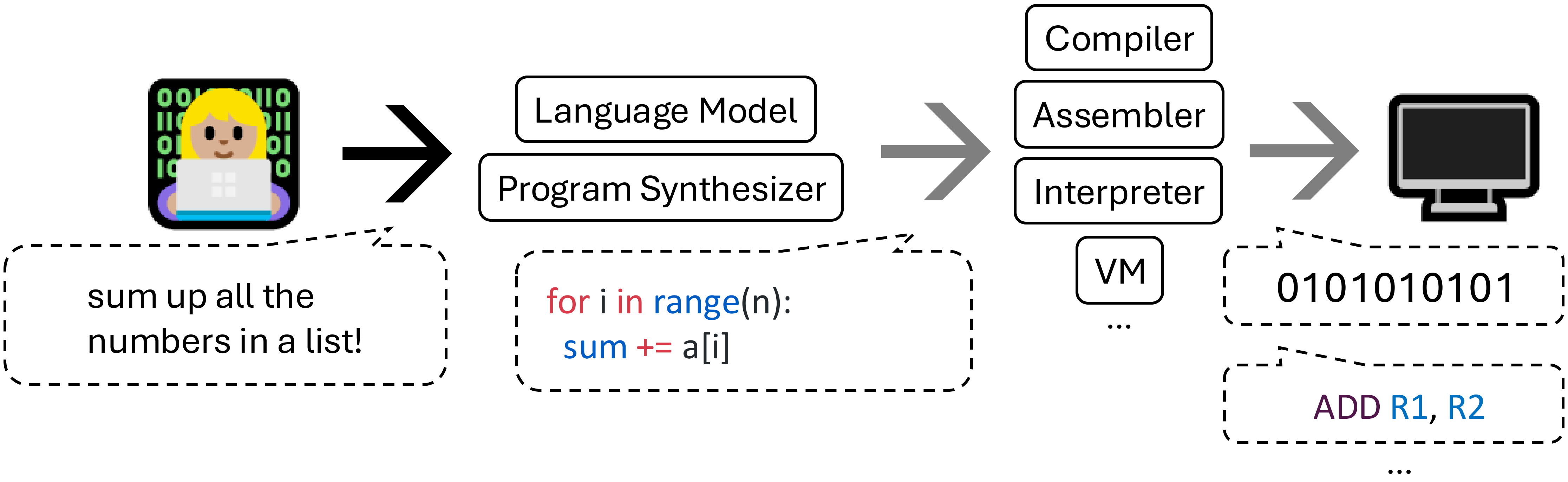
Courtesy: CSE 291 Program Synthesis – Nadia Polikarpova

Programming → Talking to Computers



Natural language as programming languages?

Programming → Talking to Computers



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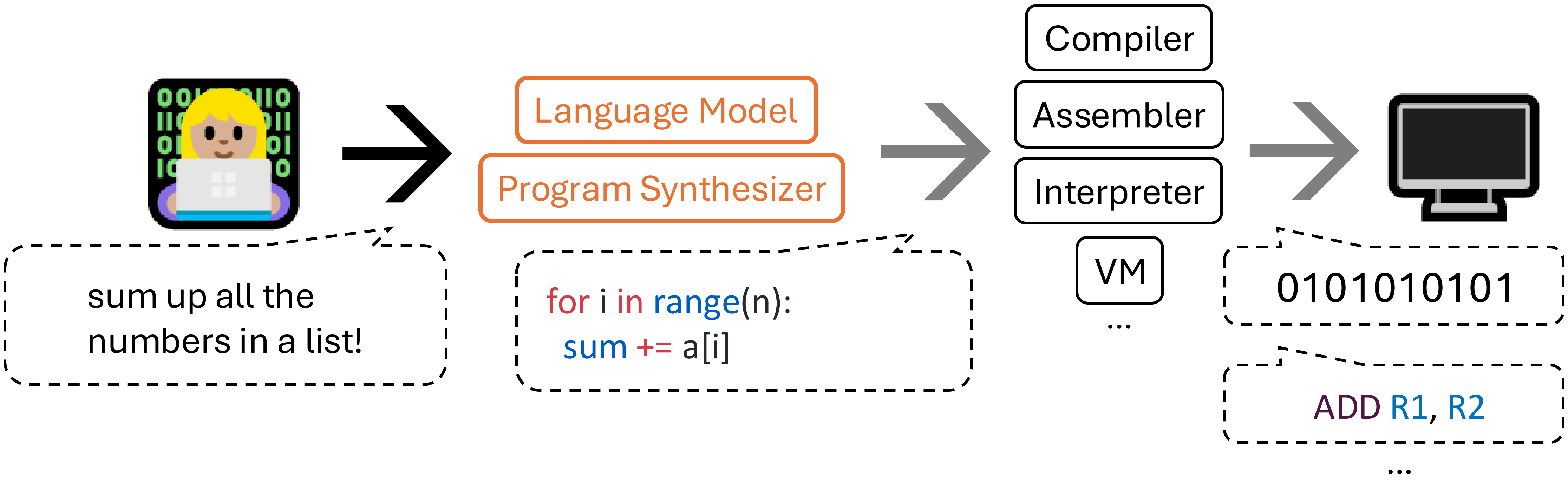

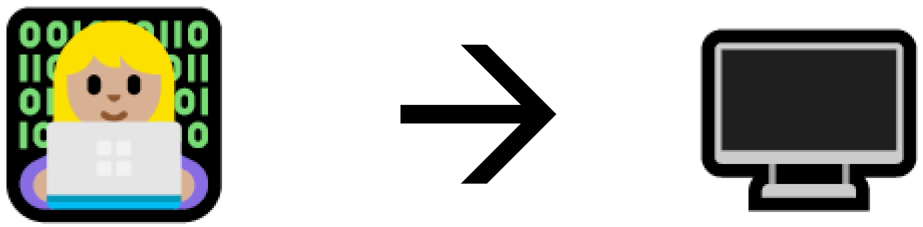

Course Roadmap & Logistics

Logistics

- Lecture
  - When: Tue/Thu 12:00 – 1:15pm
  - Where: Maryland Hall 310
- Office Hours
  - Instructor: Wed 3:00 – 4:00pm, Zoom (https://wse.zoom.us/my/ziyang)
  - TA: Tue 3:30 – 5:30pm, Malone 216
- Course Website
  - https://machine-programming.github.io
  - Discussions: courselore

Roadmap

Foundations + Applications

of machine programming

Topics

- Foundations
  - **Programming language, syntax** and **semantics**
  - **Classical synthesis**, e.g., inductive synthesis, bottom-up and top-down synthesis, type-guided synthesis, specification guided synthesis
  - **LLM-based synthesis**, e.g., natural language guided synthesis, agentic frameworks, model context protocol, language server protocol
- Applications
  - **Software Engineering & Security**, e.g., testing, transpilation, verification
  - **Math & Theorem Proving**, e.g., auto-formalization, automated proving
  - **Data Wrangling**, e.g., database querying, code querying
  - **Planning & Cyber-Physical Systems**, e.g. robotics, simulation, reward

Topics that YOU Can Explore

1. Synthesis methodologies

- Search algorithms
- Neurosymbolic method
- Feedback engineering
- Example guided synthesis
- Probabilistic method
- Human-in-the-loop synthesis / Vibe Coding

2. Foundation models

- MCP
- Reinforcement learning
- Agentic behavior
- Evaluation of coding capabilities
- Adversarial attack
- Prompting strategies
- Synthetic data generation
- Context engineering
- Fine-tuning strategies

3. Synthesis applications

- General programming
- Data wrangling
- Program repair & optimization
- Verification & security
- Scientific domains & math
- Embodied AI & robotics
- Creative coding
- Visualization, games, and graphics

4. Programming languages

- Syntax & semantics
- Type systems for synthesis
- Synthesis for domain-specific languages
- Synthesis for low-resource languages
- Language design
- Specification languages
- Language server protocal
- Safety properties

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Programming Languages

GO
Python
Java
Swift
php
C
C++
Scala
PASCAL
C#
Rust
Haskell
JS JavaScript
OCaml
julia
Common Lisp
Ruby

LaTeX
CSS
LEAN THEOREM PROVER
LLVM
HTML
ASM Assembly
Coq
Prolog
SQL
SystemVerilog
Scallop
Cg GLSL HLSL
Shell

General Purpose Programming Languages

GO

Python

Swift

php

C

C++

Java

Scala

PASCAL

C#

Rust

Haskell

JS JavaScript

OCaml

julia

Common Lisp

Ruby

LaTeX

CSS

LEAN THEOREM PROVER

LLVM

HTML

ASM Assembly

Coq

Prolog

SQL

SystemVerilog

Cg GLSL HLSL

Scallop

Shell

Domain Specific Programming Languages

GO
Python
Java
Swift
php
C
C++
Scala
PASCAL
C#
Rust
Haskell
JS JavaScript
OCaml
julia
Common Lisp
Ruby

LATEX
CSS
LEAN THEOREM PROVER
LLVM
HTML
ASM Assembly
Coq
Prolog
SQL
SystemVerilog
Scallop
Cg GLSL HLSL
Shell

Grading

- Attendance (10%)
- Assignment 1: Inductive synthesis (15%)
- Assignment 2: Evaluating coding LLMs (15%)
- Assignment 3: Coding agents (15%)
- Oral presentation (10%)
- Final Project (35%)

Assignments (45% total, 15% each)

- There will be three assignments:
  - Assignment 1: Inductive Synthesis & Basics of LLM synthesis
  - Assignment 2: Evaluating Coding LLMs
  - Assignment 3: Coding Agents
- Timeline: ~2 weeks for each assignment
- Submission: via GradeScope; submit .zip files
- Late submission: up to 3 days, -20% per day
- Extensions: possible, please request via email

Assignments (45% total, 15% each)

- Collaboration policy:
  - Encouraged, please acknowledge your collaborator
  - Still need to be your own work
- Use of AI:
  - Encouraged, please acknowledge your collaborator AI
  - Be specific about the model, version, programming environment, etc.
  - Document important conversations, learn about its good or bad

Assignments (45% total, 15% each)

- API Key for LLM use
  - Assignments will include code for you to invoke LLMs, which require API keys
  - We are going to supply an API key for Google's Gemini Model
    - The key will be sent privately to each of you via email
  - Do not share API key with others, even your collaborators
  - We keep track of API usage (#requests, #tokens, $, etc.)
  - Overused API key will be revoked

Oral Presentation (10%)

- Happening on the latter half of the semester
- Two students will be paired to explore the direction of that week
  - Each one will read a paper within the direction
  - The paper could be from the list or proposed by yourself (talk to me!)
  - Lead a 25min in-class discussion; 15-20min presentation & 5-10min Q&A
- A presentation sign-up form will be sent out later

Final Project

- On any aforementioned topics
  - Re-implement a technique from a paper
  - Applying existing synthesis framework to a new domain
  - Extend/improve existing synthesis algorithm or tool
  - Develop a new synthesis algorithm or tool
  - New dataset, new benchmark, or a novel evaluation
  - …
- Judged in terms of
  - Quality of execution
  - Originality
  - Scope

Final Project

Team forming

Team of 2/3 people
- Pick a project when you are forming the team!
- Talk to the instructor and the TA for project ideas

Proposal

A document of 1-2 pages
- Team members
- Explain what you plan to do and give some evidence that you can make it

Presentation

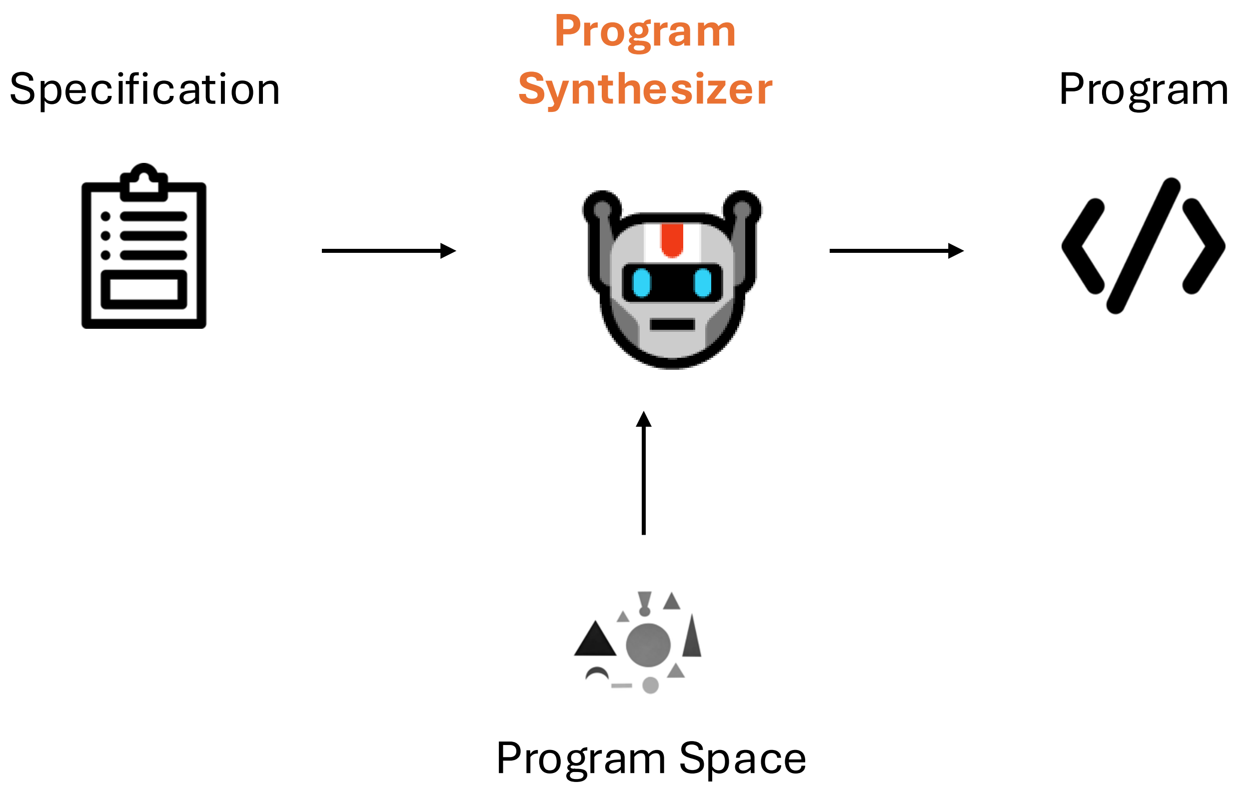
A presentation of 15min (10min presentation + 5min Q&A)
- During the finals week
- Talk about motivation, scope, progress, and results
- Discuss future works

Report

A 4-8 pages document, structured like a research paper

Program Synthesis

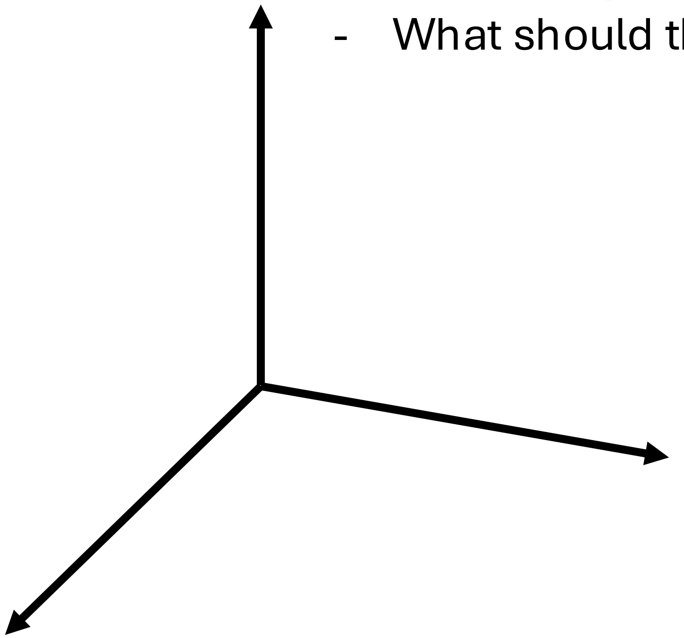
Program Synthesizers



Dimensions in Program Synthesis

Behavioral Specification

- What should the program do?



Synthesis Strategy

- How do we find such a program?

Structural Specification

- What is the space of the programs?

Dimensions in Program Synthesis

Behavioral Specification
- What should the program do?

Examples:
- input/output examples, test cases
- reference implementation / pseudo code
- formal statements (pre-/post-cond., types, constraints)
- natural language description, comments
- ...

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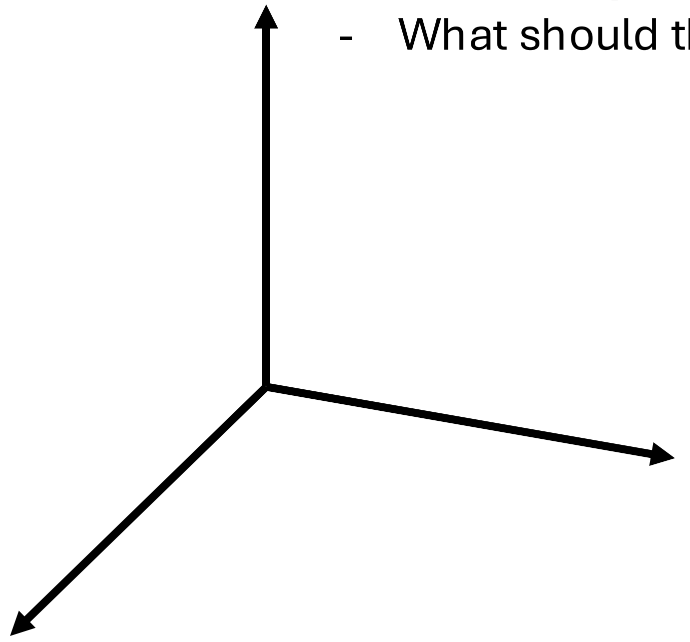
Dimensions in Program Synthesis



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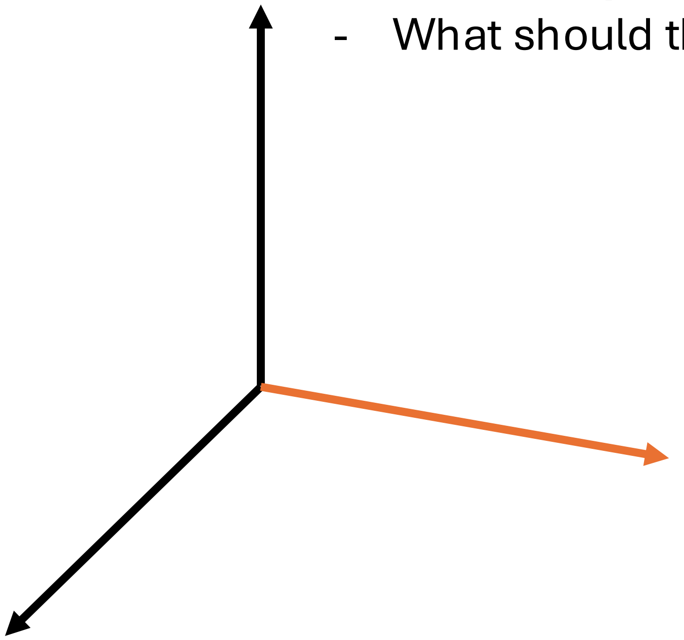

Structural Specification
- What is the space of the programs?

Examples:
- Language syntax / grammar
- User-defined domain specific language
- Templates / generators
- Built-in / custom operators

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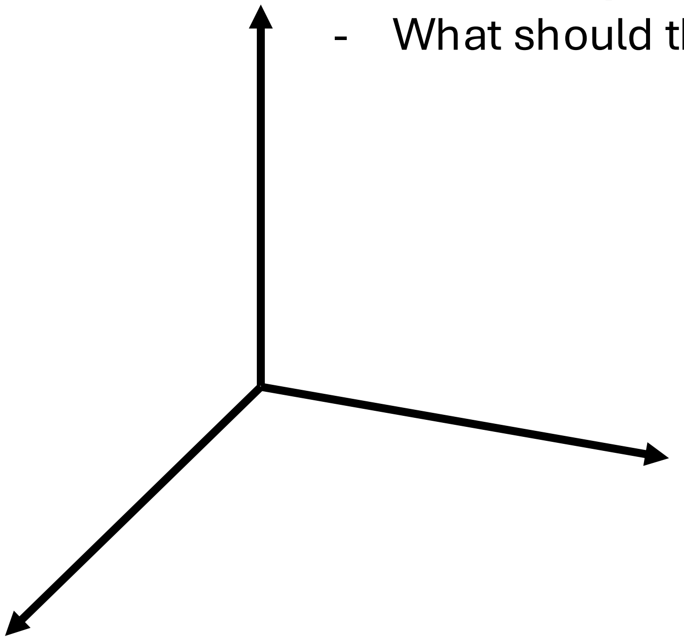
- How do we find such a program?

Dimensions in Program Synthesis

Behavioral Specification
- What should the program do?



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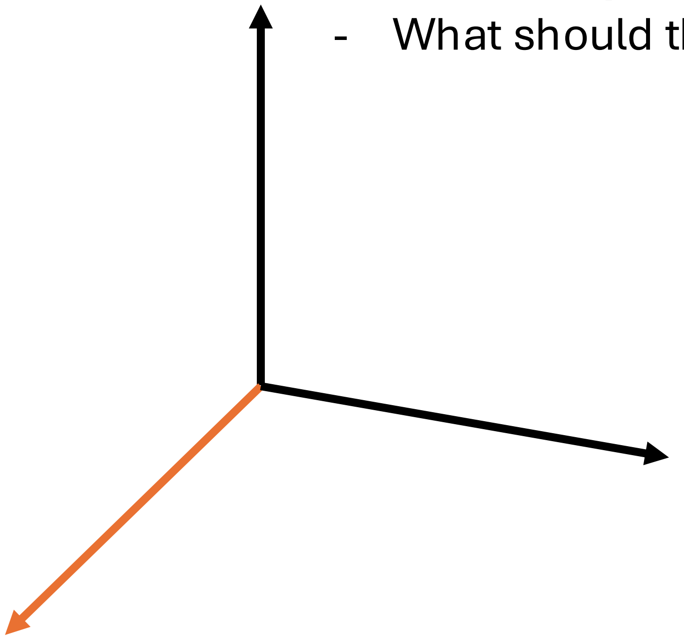
Structural Specification
- What is the space of the programs?

Dimensions in Program Synthesis

Behavioral Specification

- What should the program do?



Synthesis Strategy

- How do we find such a program?

Examples:

- Bottom-up / top-down search
- Stochastic / constraint-based search
- LLM zero-shot / few-shot prompting
- Chain-of-thought reasoning
- Iterative / agentic self-refinement

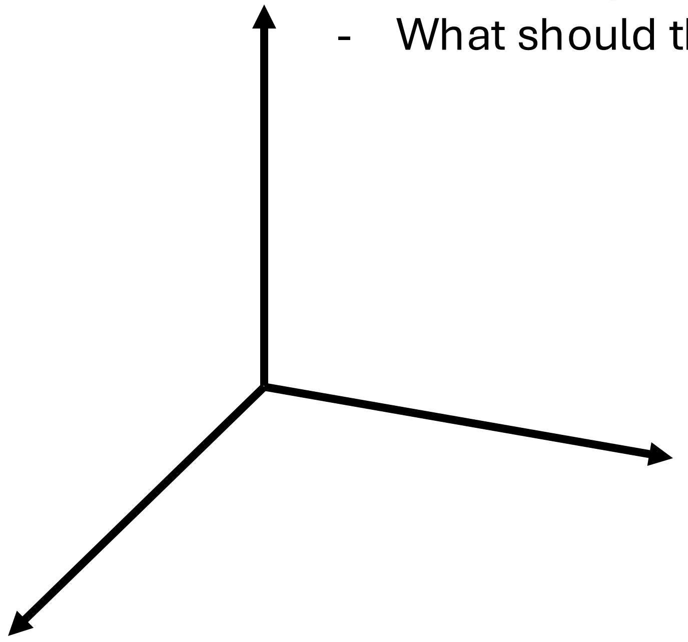
Structural Specification

- What is the space of the programs?

Dimensions in Program Synthesis

Behavioral Specification

- What should the program do?



Synthesis Strategy

- How do we find such a program?

Structural Specification

- What is the space of the programs?

Structure of the course

- Module 1: Foundations of Program Synthesis
  - Programming language syntax and semantics
  - Classical methods for synthesizing programs
- Module 2: Program Synthesis in the era of Foundation Models
  - Prompting strategies, evaluating coding LLMs
  - Iterative synthesis, MCP and tool use, agentic program synthesis
- Module 3: Applications of Program Synthesis
  - Software engineering, theorem proving, planning, interactive
  - Other advanced topics

Week 1

- Topic:
  - Programming language syntax & semantics
  - Bottom-up enumerative synthesis from examples
- Assignment 1:
  - Released: https://github.com/machine-programming/assignment-1
  - API keys will be sent shortly
  - Submission on GradeScope will be opened next Tuesday