Instruction Sets and Code Generation

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This Lecture

Operational Semantics

- of ChocoPy

Machine Architecture

- components of a (virtual) machine

RISC-V Instruction Set

- instructions, registers, conventions

Code Generation by Term Transformation

- from source AST to target AST

Compilation Schemas

- how do source language constructs map to machine code

Operational Semantics

Operational Semantics

6 Operational semantics

This section contains the formal operational semantics for the ChocoPy language.

The operational semantics define how every definition, statement, or expression in a ChocoPy program should be evaluated in a given context.

Literals

$$\frac{}{G, E, S \vdash \texttt{None} : None, S, \_} \quad \text{[NONE]}$$

$$\frac{}{G, E, S \vdash \texttt{False} : bool(false), S, \_} \quad \text{[BOOL-FALSE]}$$

$$\frac{}{G, E, S \vdash \texttt{True} : bool(true), S, \_} \quad \text{[BOOL-TRUE]}$$

$$\frac{i \text{ is an integer literal}}{G, E, S \vdash i : int(i), S, \_} \quad \text{[INT]}$$

$$\frac{\begin{array}{l} s \text{ is a string literal} \\ n \text{ is the length of the string } s \end{array}}{G, E, S \vdash s : str(n, s), S, \_} \quad \text{[STR]}$$

Expression Statement

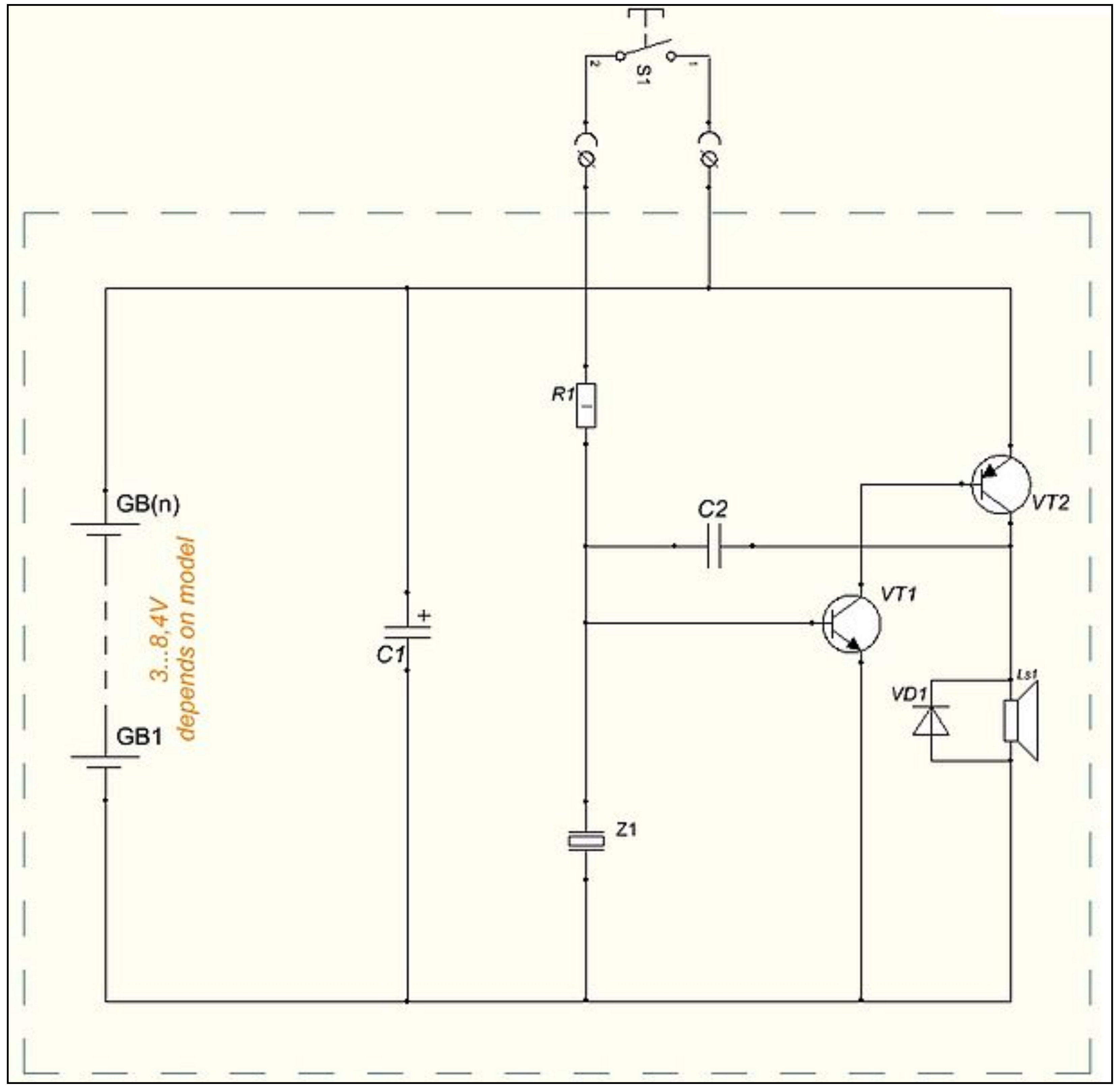
$$\frac{G, E, S \vdash e : v, S', \_}{G, E, S \vdash e : \_, S', \_} \quad [\text{EXPR-STMT}]$$

Arithmetic Expressions

$$\frac{G, E, S \vdash e : int(i_1), S_1, \_ \quad v = int(-i_1)}{G, E, S \vdash \texttt{-}\ e : v, S_1, \_} \quad [\text{NEGATE}]$$

$$\frac{\begin{array}{l} G, E, S \vdash e_1 : int(i_1), S_1, \_ \\ G, E, S_1 \vdash e_2 : int(i_2), S_2, \_ \\ op \in \{\texttt{+}, \texttt{-}, \texttt{*}, \texttt{//}, \texttt{\%}\} \\ op \in \{\texttt{//}, \texttt{\%}\} \Rightarrow i_2 \neq 0 \\ v = int(i_1\ op\ i_2) \end{array}}{G, E, S \vdash e_1\ op\ e_2 : v, S_2, \_} \quad [\text{ARITH}]$$

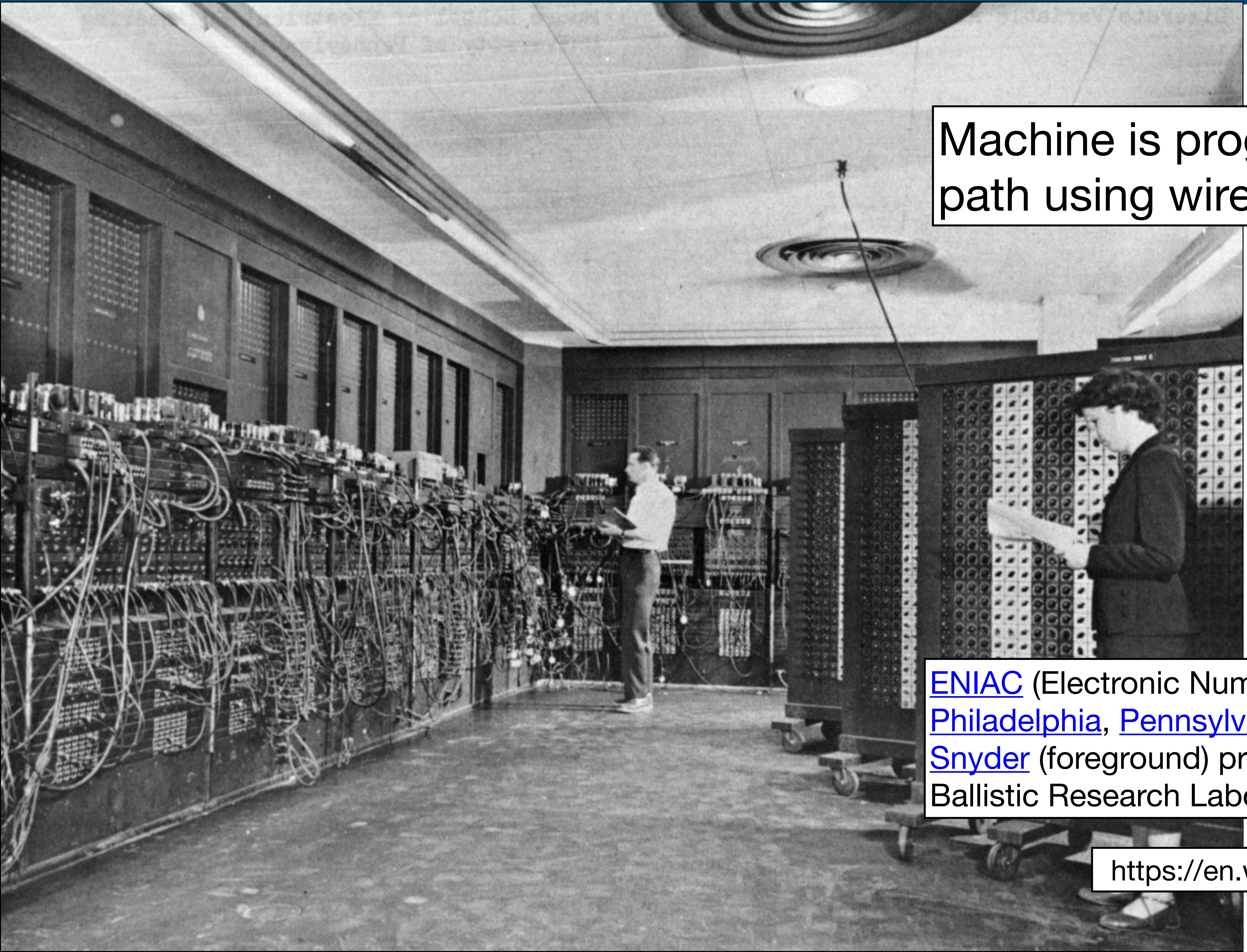
Machine Architecture



Fixed to perform one computation from input to output

https://commons.wikimedia.org/wiki/File:Wiring_diagram_of_battery-powered_doorbell.JPG

Programmable Machines



Machine is programmed by creating data path using wires

ENIAC (Electronic Numerical Integrator And Computer) in Philadelphia, Pennsylvania. Glen Beck (background) and Betty Snyder (foreground) program the ENIAC in building 328 at the Ballistic Research Laboratory (BRL).

https://en.wikipedia.org/wiki/ENIAC#/media/File:Eniac.jpg

Stored-Program Computer (Von Neumann Architecture)

Central Processing Unit

- Processor registers
- Arithmetic logic unit

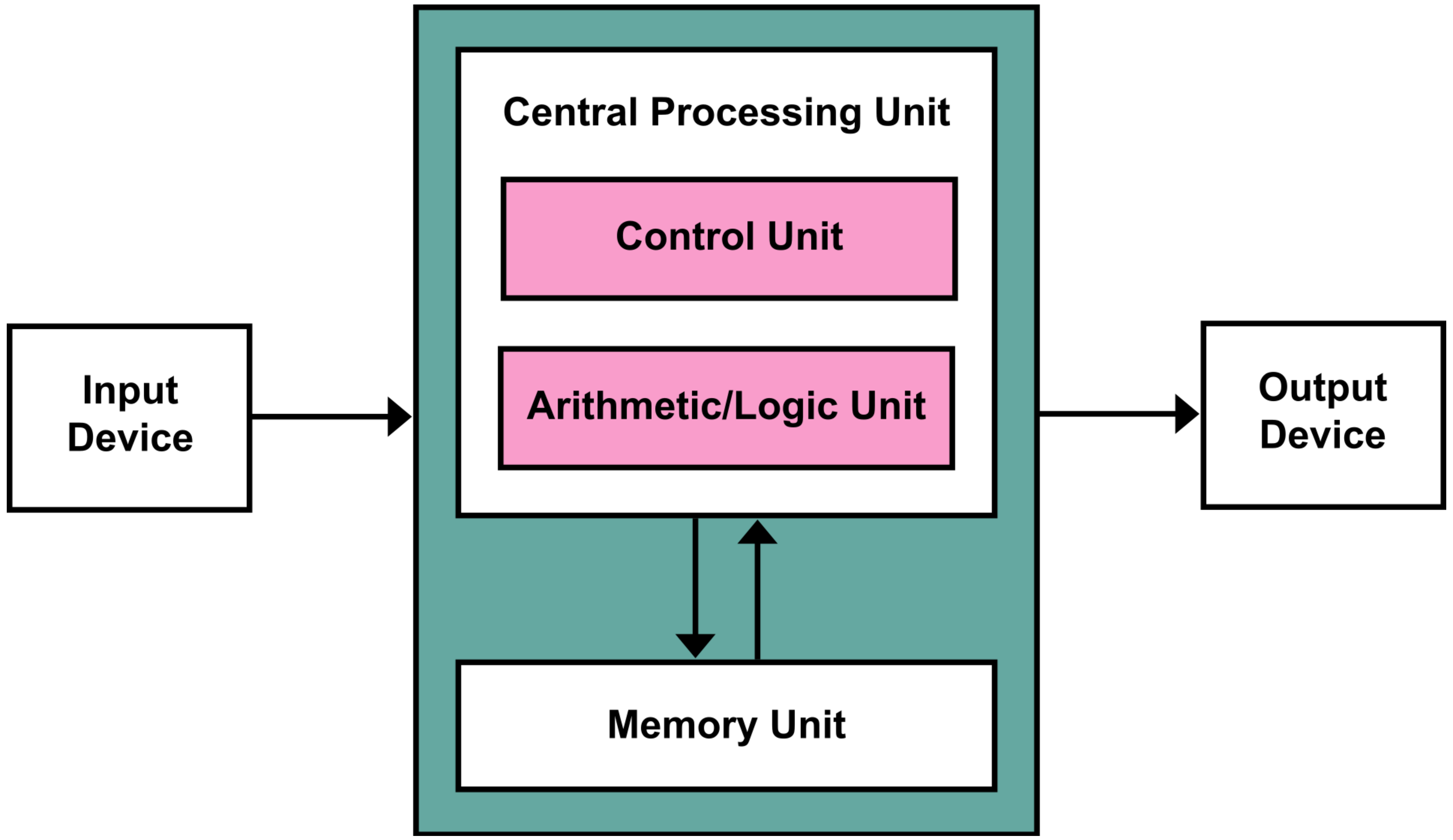
Main Memory

- Stores data and instructions

External Storage

- Persistent storage of data

Input/Output



https://en.wikipedia.org/wiki/Von_Neumann_architecture#/media/File:Von_Neumann_Architecture.svg

State

Machine state

- data stored in memory
- memory hierarchy: registers, RAM, disk, network, …

Imperative program

- computation is series of changes to memory
- basic operations on memory (increment register)
- controlling such operations (jump, return address, …)
- control represented by state (program counter, stack, …)

Example: x86 Assembler

`mov AX [1]`	read memory
`mov CX AX`	
`L: dec CX`	
`mul CX`	calculation
`cmp CX 1`	
`ja L`	jump
`mov [2] AX`	write memory

Example: Java Bytecode

```
.method static public m(I)I

        iload 1
        ifne else          jump
        iconst_1
        ireturn

else:   iload 1            read memory
        dup
        iconst_1
        isub               calculation
        invokestatic Math/m(I)I
        imul
        ireturn
```

Memory & Control Abstractions

Memory abstractions

- variables: abstract over data storage
- expressions: combine data into new data
- assignment: abstract over storage operations

Control-flow abstractions

- structured control-flow: abstract over unstructured jumps
- ‘go to statement considered harmful’ Edgser Dijkstra, 1968

Example: C

```
int f = 1
int x = 5
int s = f + x

while (x > 1) {
   f = x * f ;
   x = x - 1
}
```

variable

expression

control flow

assignment

Procedural Abstraction

Control-flow abstraction

- Procedure: named unit of computation
- Procedure call: jump to unit of computation and return

Memory abstraction

- Formal parameter: the name of the parameter
- Actual parameter: value that is passed to procedure
- Local variable: temporary memory

Recursion

- Procedure may (indirectly) call itself
- Consequence?

RISC-V Instruction Set

Concrete Syntax

```
.globl main
main:
  lui a0, 8192                         # Initialize heap size (in multiples of 4KB)
  add s11, s11, a0                     # Save heap size
  jal heap.init                        # Call heap.init routine
  mv gp, a0                            # Initialize heap pointer
  mv s10, gp                           # Set beginning of heap
  add s11, s10, s11                    # Set end of heap (= start of heap + heap size)
  mv ra, zero                          # No normal return from main program.
  mv fp, zero                          # No preceding frame.
  mv fp, zero                          # Top saved FP is 0.
  mv ra, zero                          # No function return from top level.
  addi sp, sp, -@..main.size           # Reserve space for stack frame.
  sw ra, @..main.size-4(sp)            # return address
  sw fp, @..main.size-8(sp)            # control link
  addi fp, sp, @..main.size            # New fp is at old SP.
  jal initchars                        # Initialize one-character strings.
  li a0, 1                             # Load boolean literal: true
  beqz a0, label_1                     # Operator and: short-circuit left operand
  li a0, 0                             # Load boolean literal: false
  seqz a0, a0                          # Logical not
label_1:                               # Done evaluating operator: and
  .equiv @..main.size, 16
label_0:                               # End of program
  li a0, 10                            # Code for ecall: exit
  ecall
```

Syntax Definition (*)

```
// RV32I - Base
// Math
Instruction.Add  = <add  <ID>, <ID>, <ID>>      {case-insensitive}
Instruction.Addi = <addi <ID>, <ID>, <IntOrID>> {case-insensitive}
Instruction.And  = <and  <ID>, <ID>, <ID>>      {case-insensitive}
Instruction.Andi = <andi <ID>, <ID>, <IntOrID>> {case-insensitive}
Instruction.Or   = <or   <ID>, <ID>, <ID>>      {case-insensitive}
Instruction.Ori  = <ori  <ID>, <ID>, <IntOrID>> {case-insensitive}
Instruction.Xor  = <xor  <ID>, <ID>, <ID>>      {case-insensitive}
Instruction.Xori = <xori <ID>, <ID>, <IntOrID>> {case-insensitive}
Instruction.Sub  = <sub  <ID>, <ID>, <ID>>      {case-insensitive}

// Branches
Instruction.Beq  = <beq <ID>, <ID>, <IntOrID>>  {case-insensitive}
Instruction.Bne  = <bne <ID>, <ID>, <IntOrID>>  {case-insensitive}
Instruction.Blt  = <blt <ID>, <ID>, <IntOrID>>  {case-insensitive}
Instruction.Bge  = <bge <ID>, <ID>, <IntOrID>>  {case-insensitive}
Instruction.Bltu = <bltu <ID>, <ID>, <IntOrID>> {case-insensitive}
Instruction.Bgeu = <bgeu <ID>, <ID>, <IntOrID>> {case-insensitive}

// Misc.
Instruction.Ecall = <ecall>
Instruction.Lui   = <lui   <ID>, <IntOrID>> {case-insensitive}
Instruction.Auipc = <auipc <ID>, <IntOrID>> {case-insensitive}

// Jumps
Instruction.Jal  = <jal  <ID>, <IntOrID>>       {case-insensitive}
Instruction.Jalr = <jalr <ID>, <ID>, <IntOrID>> {case-insensitive}
```

RV32IM.sdf3

Abstract Syntax Signature (*)

```
module signatures/RV32IM-sig

imports signatures/Common-sig

signature
  sorts Start Line Label Statement Pseudodirective Instruction IntOrID
  constructors
    Program                 : List(Line) → Start
                            : Statement → Line
                            : Label → Line
    Label                   : ID → Label
                            : INT → IntOrID
                            : ID → IntOrID
                            : Pseudodirective → Statement
                            : Instruction → Statement
    PSData                  : Pseudodirective
    PSText                  : Pseudodirective
    PSString                : STRING → Pseudodirective
    PSAsciiz                : STRING → Pseudodirective
    PSWord                  : List(IntOrID) → Pseudodirective
    PSSpace                 : INT → Pseudodirective
    …
    Add                     : ID * ID * ID → Instruction
    Addi                    : ID * ID * IntOrID → Instruction
    And                     : ID * ID * ID → Instruction
    Andi                    : ID * ID * IntOrID → Instruction
    Or                      : ID * ID * ID → Instruction
    Ori                     : ID * ID * IntOrID → Instruction
    …
```

RV32IM-sig.str

RISC-V Assembly Programmer's Manual

Load Immediate

The following example shows the `li` pseudo instruction which is used to load immediate values:

```
        .equ    CONSTANT, 0xdeadbeef

        li      a0, CONSTANT
```

Which, for RV32I, generates the following assembler output, as seen by `objdump`:

```
00000000 <.text>:
   0:   deadc537                lui     a0,0xdeadc
   4:   eef50513                addi    a0,a0,-273 # deadbeef <CONSTANT+0x0>
```

https://github.com/riscv/riscv-asm-manual/blob/master/riscv-asm.md

RISC-V Assembly Programmer's Manual

Load Address

The following example shows the `la` pseudo instruction which is used to load symbol addresses:

```
        la      a0, msg + 1
```

Which generates the following assembler output and relocations for non-PIC as seen by `objdump`:

```
0000000000000000 <.text>:
   0:   00000517                auipc   a0,0x0
                        0: R_RISCV_PCREL_HI20   msg+0x1
   4:   00050513                mv      a0,a0
                        4: R_RISCV_PCREL_LO12_I .L0
```

And generates the following assembler output and relocations for PIC as seen by `objdump`:

```
0000000000000000 <.text>:
   0:   00000517                auipc   a0,0x0
                        0: R_RISCV_GOT_HI20     msg+0x1
   4:   00053503                ld      a0,0(a0) # 0 <.text>
                        4: R_RISCV_PCREL_LO12_I .L0
```

https://github.com/riscv/riscv-asm-manual/blob/master/riscv-asm.md

From Concrete Syntax to Abstract Syntax (*)

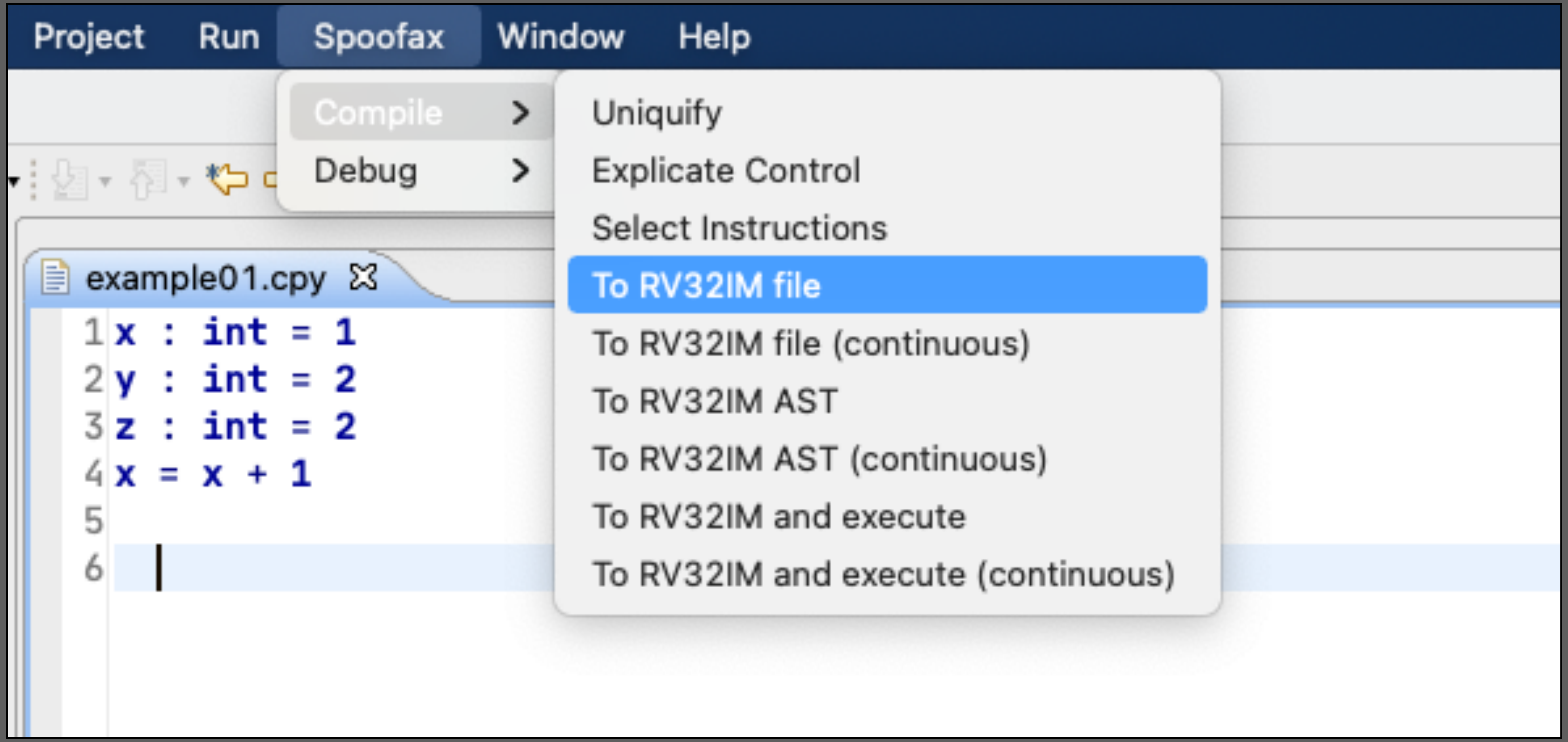
```
.text

li a0, 1
li a1, 15
ecall

li a0, 10
ecall
```

```
Program(
  [ PSText()
  , Li("a0", "1")
  , Li("a1", "15")
  , Ecall()
  , Li("a0", "10")
  , Ecall()
  ]
)
```

Code Generation by Term Transformation

Compilation Menu: chocopy.cfg

```
editor-context-menu [
  menu "Compile" [
    command-action {
      command-def = uniquifyToAstCommand
      execution-type = Once
      required-enclosing-resource-types = [Project]
    }
    command-action {
      command-def = explicateControlToAstCommand
      execution-type = Once
      required-enclosing-resource-types = [Project]
    }
    command-action {
      command-def = selectInstructionsToAstCommand
      execution-type = Once
      required-enclosing-resource-types = [Project]
    }
    command-action {
      command-def = toFileCommand
      execution-type = Once
      required-enclosing-resource-types = [Project]
    }
    command-action {
      command-def = toFileCommand
      execution-type = Continuous
      required-enclosing-resource-types = [Project]
    }
```



Invoking the Compiler: chocopy.cfg

```
let toFile = task-def mb.chocopy.show.ShowCompileToRv32ImFile
let toFileCommand = command-def {
  task-def = toFile
  display-name = "To RV32IM file"
  parameters = [
    rootDirectory = parameter {
      type = java mb.resource.hierarchical.ResourcePath
      argument-providers = [EnclosingContext(Project)]
    }
    file = parameter {
      type = java mb.resource.hierarchical.ResourcePath
      argument-providers = [Context(File)]
    }
  ]
}
```

Invoking the Compiler: Java

```java
package mb.chocopy.show;

import …

@ChocopyScope
public class ShowCompileToRv32ImFile implements TaskDef<ShowCompileToRv32ImFile.Args, CommandFeedback> {
    @SuppressWarnings("serial")     public static final class Args implements Serializable {
        public final ResourcePath rootDirectory;
        public final ResourcePath file;
        public Args(ResourcePath rootDirectory, ResourcePath file) {
            this.rootDirectory = rootDirectory;
            this.file = file;
        }
        @Override public boolean equals(@Nullable Object o) {
            if(this == o) return true;
            if(o == null || getClass() != o.getClass()) return false;
            Args input = (Args)o;
            if(!rootDirectory.equals(input.rootDirectory)) return false;
            return file.equals(input.file);
        }
        @Override public int hashCode() {
            int result = rootDirectory.hashCode();
            result = 31 * result + file.hashCode();
            return result;
        }
        @Override public String toString() {
            return "ShowCompileToRv32ImFile$Args{" +
                "rootDirectory=" + rootDirectory +
                ", file=" + file +
                '}';
        }
    }

    private final ChocopyAnalyzeFile analyzeFile;
    private final CompileToRv32ImText compileToRv32ImText;

    @Inject public ShowCompileToRv32ImFile(
            ChocopyAnalyzeFile analyzeFile,
            CompileToRv32ImText compileToRv32ImText
       ) {
       this.analyzeFile = analyzeFile;
       this.compileToRv32ImText = compileToRv32ImText;
       }
```

```java
       @Override public CommandFeedback exec(ExecContext context, Args args) throws IOException {
        final ResourcePath file = args.file;
              return context.require(compileToRv32ImText.createSupplier(analyzeFile.createSupplier(new ChocopyAnalyzeFile.Input(args.rootDirectory,
                                                                                                                                   args.file)))).mapThrow

             text -> {
              final ResourcePath outputFilePath = file.appendToLeafExtension("rv32im");
              final WritableResource outputFile = context.getWritableResource(outputFilePath);
              outputFile.writeString(text);
              context.provide(outputFile);
              return CommandFeedback.of(ShowFeedback.showFile(outputFilePath));
              },
              e -> CommandFeedback.ofTryExtractMessagesFrom(e, file)
              );
       }

       @Override public String getId() {
              return getClass().getName();
       }
}
```

The Compiler Pipeline

```
rules

  compile-to-rv32im-ast :: Program → RProgram

  compile-to-rv32im-ast =
    compile-cpy-to-cir
    ; compile-cir-to-rv32im
    ; compile-rv32im
```

```
rules

  compile-cpy-to-cir :: Program → CProgram

  compile-cpy-to-cir =
    explicate-types
    ; desugar
    ; uniquify
    ; remove-complex-operands
    ; explicate-control
```

```
  compile-cir-to-rv32im :: CProgram → RProgram

  compile-cir-to-rv32im =
    select-instructions-cprogram
```

```
  compile-rv32im :: RProgram → RProgram

  compile-rv32im =
    assign-homes
    ; patch-instructions
```

Uniquify

Uniquify

```
x : int = 1
y : int = 2
z : int = 2
x = x + 1
z = x + y
```

```
Program(
  [ VarDef(TypedVar("x3", Type("int")), Int("1"))
  , VarDef(TypedVar("y3", Type("int")), Int("2"))
  , VarDef(TypedVar("z1", Type("int")), Int("2"))
  ]
, [ Assign(
      [Target(Var("x3"))]
    , Add(Var("x3"), Int("1"))
    )
  , Assign(
      [Target(Var("z1"))]
    , Add(Var("x3"), Var("y3"))
    )
  ]
)
```

Uniquify

```
rules

  declare-new-name :: ID → ID

  declare-new-name :
    x1 → x2
    with <newname> x1 ⇒ x2
    with rules( Rename : x1 → x2 )

  rename :: string → string
  rename :
    x1 → x2
    with <stx-get-ast-analysis> x1 ⇒ analysis
    with <stx-get-ast-ref(|analysis)
          ; if is-list then Hd end> x1 ⇒ d
    where <Rename>d ⇒ x2
```

```
rules

  uniquify      :: Program → Program
  uniquify-gen  :: ? → ?
  uniquify-def  :: Definition → Definition
  uniquify-ref  :: Var → Var

  uniquify =
    uniquify-gen

  uniquify-gen =
    topdown(try(is(Definition); uniquify-def))
    ; topdown(try(is(Var); uniquify-ref))

  uniquify-def :
    VarDef(TypedVar(x1, t), e1) → VarDef(TypedVar(x2, t), e1)
    with <declare-new-name> x1 ⇒ x2

  uniquify-ref :
    Var(x1) → Var(x2)
    where <rename> x1 ⇒ x2
```

C-IR

‘C’ Intermediate Representation

```
signature
  sorts CID CINT CProgram CBlock CLabel CTail CStmt
        CType CExp CAtom CVar
  constructors
                      : string → CID
                      : string → CINT
    CProgram          : List(CBlock) → CProgram
    CBlock            : CLabel * CTail → CBlock
    CLabel            : CID → CLabel
    CReturn           : CExp → CTail
    CReturnNone       : CTail
    CSeq              : CStmt * CTail → CTail
    CVarDec           : CVar * CType * CExp → CStmt
    CAssign           : CVar * CExp → CStmt
    CIntT             : CType
                      : CAtom → CExp
    CRead             : CExp
    CMin              : CAtom → CExp
    CAdd              : CAtom * CAtom → CExp
    CMul              : CAtom * CAtom → CExp
    CDiv              : CAtom * CAtom → CExp
    CInt              : CINT → CAtom
                      : CVar → CAtom
    CVar              : CID → CVar
```

Explicate Control: Generating a Control-Flow Graph

```
rules // control-flow graph

  add-cfg-node  :: CBlock → CBlock
  all-cfg-nodes :: List(CBlock) → List(CBlock)

  add-cfg-node =
    ?block
    ; rules( CFGNode :+ _ → block )

  all-cfg-nodes =
    <bagof-CFGNode <+ ![]>()
```

```
rules

  explicate-control :: Program → CProgram

  explicate-control :
    Program(defs, stms)  → CProgram([CBlock(CLabel("Main"), tail2) | blocks])
    with <explicate-tail-seq> stms ⇒ tail1
    with <explicate-defs(|tail1)> defs ⇒ tail2
    with <all-cfg-nodes>[] ⇒ blocks
```

Instruction Selection

Select Instructions: Example

```
z : int = 3
z + 1
```

```
CProgram(
  [ CBlock(
      CLabel("Main")
    , CSeq(
        CVarDec(CVar("z4"), CIntT(), CInt("3"))
      , CReturn(CAdd(CVar("z4"), CInt("1")))
      )
    )
  ]
)
```

```
RProgram(
  [ RPSData()
  , RPSText()
  , RLabel("Main")
  , RLocal(RVar("z3"), RIntT())
  , RLi(RVar("z3"), RInt("3"))
  , RAddi(RReg("a0"), RVar("z3"), RInt("1"))
  ]
)
```

Select Instructions: Programs

```
rules select-instructions-cprogram :: CProgram → RProgram

  select-instructions-cprogram :
    CProgram(blocks) → RProgram(<concat>[
      [RPSData()],
      [RPSText()],
      instrs
    ])
   with <mapconcat(select-instrs-block(|"a0"))> blocks ⇒ instrs
```

```
rules select-instrs-block(|string) :: CBlock → List(RLine)

  select-instrs-block(|r) :
    CBlock(CLabel(lbl), tail) → [RLabel(<cid-to-string>lbl) | instrs]
    with <select-instrs-tail(|RReg("a0"))> tail ⇒ instrs

rules select-instrs-tail(|RArg) :: CTail → List(RLine)

  select-instrs-tail(|r) :
    CReturn(exp) → instrs
    with <select-instrs-exp(|r)> exp ⇒ instrs

  select-instrs-tail(|r) :
    CReturnNone() → []
```

Select Instructions: Programs

```
rules select-instructions-cprogram :: CProgram → RProgram

  select-instructions-cprogram :
    CProgram(blocks) → RProgram(<concat>[
      [RPSData()],
      [RPSText()],
      instrs
    ])
   with <mapconcat(select-instrs-block(|"a0"))> blocks ⇒ instrs
```

```
rules select-instrs-block(|string) :: CBlock → List(RLine)

  select-instrs-block(|r) :
    CBlock(CLabel(lbl), tail) → [RLabel(<cid-to-string>lbl) | instrs]
    with <select-instrs-tail(|RReg("a0"))> tail ⇒ instrs

rules select-instrs-tail(|RArg) :: CTail → List(RLine)

  select-instrs-tail(|r) :
    CReturn(exp) → instrs
    with <select-instrs-exp(|r)> exp ⇒ instrs

  select-instrs-tail(|r) :
    CReturnNone() → []
```

Select Instructions: Expressions

```
rules select-instrs-exp(|RArg) :: CExp → List(RLine)

  select-instrs-exp(|x) :
    CInt(i) → [RLi(x, <cint-to-rint>i)]

  select-instrs-exp(|x) :
    CVar(y) → [RMv(x, RVar(<cid-to-string>y))]

  select-instrs-exp(|x) :
    CAdd(y@CVar(_), z@CVar(_)) → [RAdd(x, <cvar-to-rvar>y, <cvar-to-rvar>z)]
```

Compilation Schemas

Abstract From Implementation Details

$|[\ i\ ]|_{r,regs} \Rightarrow$ `li r, i`

$|[\ e + i\ ]|_{r,regs} \Rightarrow |[\ e\ ]|_{r,regs}$
`addi r, r, i`

$|[\ e1 + e2\ ]|_{r1,r2,regs} \Rightarrow |[\ e1\ ]|_{r1,r2,regs}$
$|[\ e2\ ]|_{r2,regs}$
`add r1, r1, r2`