Compiler
Construction

LA

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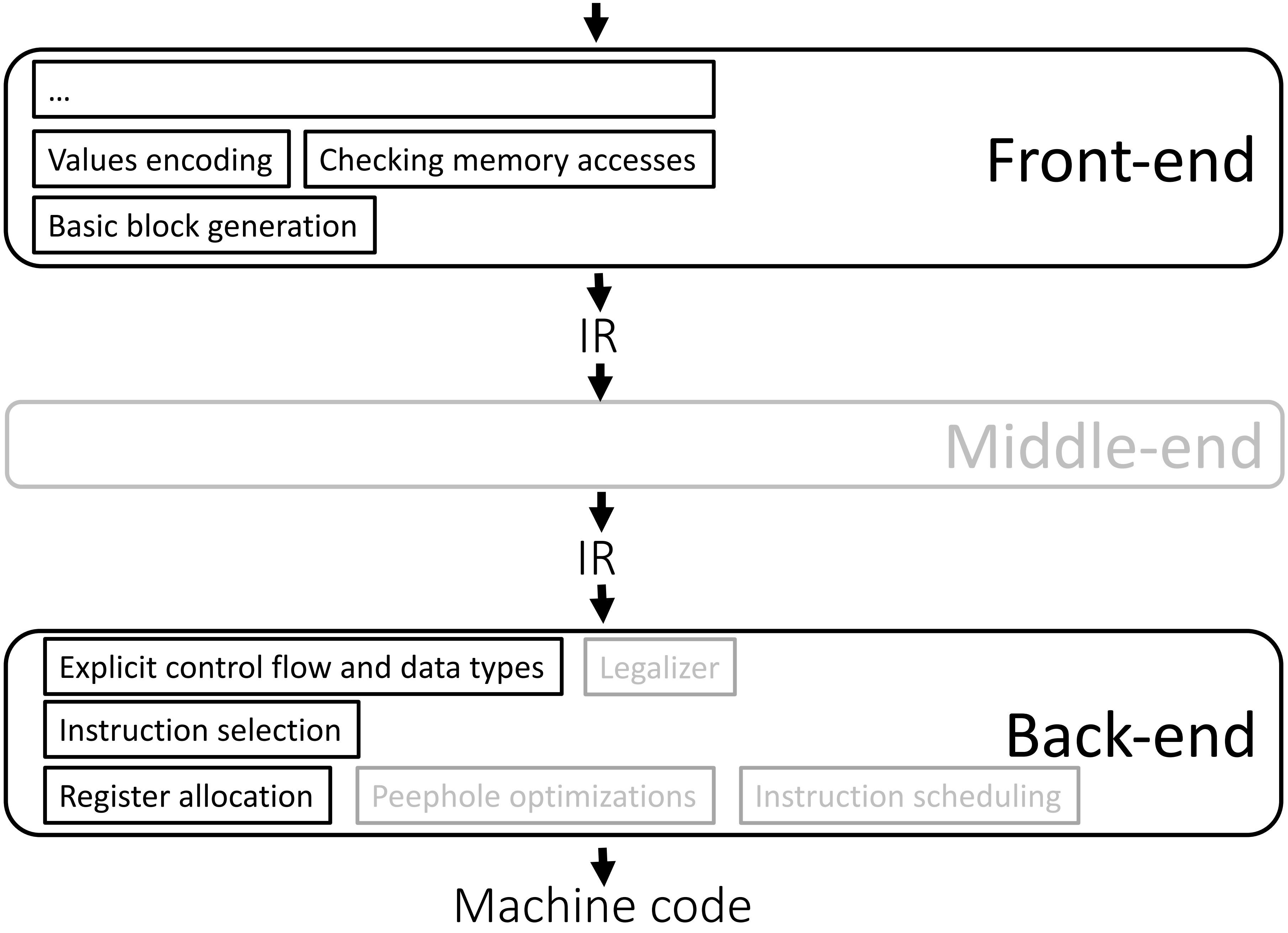
A compiler


High level programming language

...

Values encoding

Checking memory accesses

Basic block generation

Front-end

IR

Middle-end

IR

Explicit control flow and data types

Legalizer

Instruction selection

Register allocation

Peephole optimizations

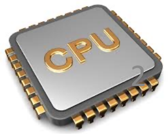
Instruction scheduling

Back-end

Machine code

The Code Developer

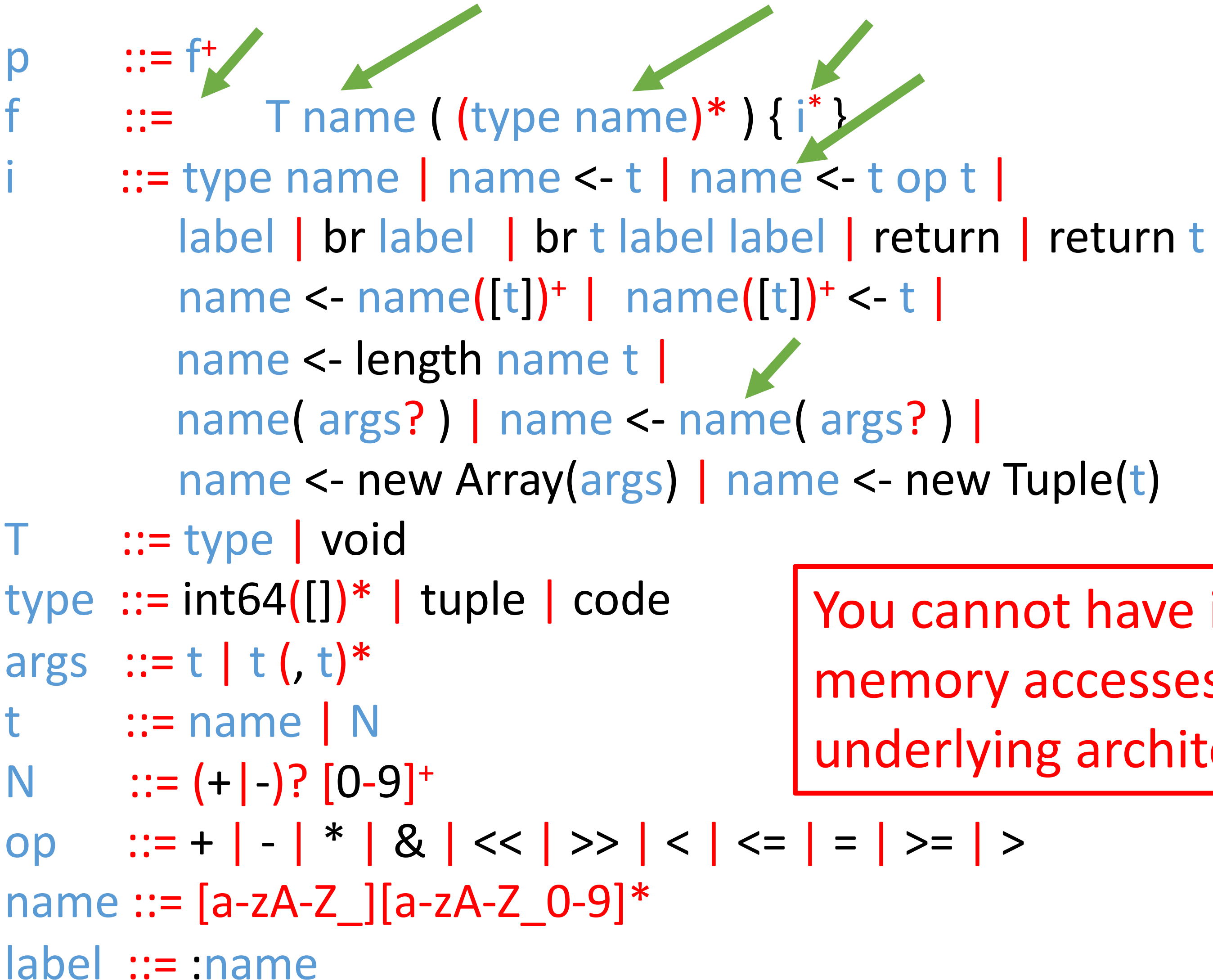
Code analysis and transformation



Outline

- LA
- Encoding values
- Checking array accesses
- Generating basic blocks and variable definitions

LA



```
p       ::= f+
f       ::=       T name ( (type name)* ) { i* }
i       ::= type name | name <- t | name <- t op t |
            label | br label  | br t label label | return | return t
            name <- name([t])+ |  name([t])+ <- t |
            name <- length name t |
            name( args? ) | name <- name( args? ) |
            name <- new Array(args) | name <- new Tuple(t)
T       ::= type | void
type    ::= int64([])* | tuple | code
args    ::= t | t (, t)*
t       ::= name | N
N       ::= (+|-)? [0-9]+
op      ::= + | - | * | & | << | >> | < | <= | = | >= | >
name ::= [a-zA-Z_][a-zA-Z_0-9]*
label  ::= :name
```

You cannot have invalid memory accesses in the underlying architecture

All values are decoded!

```
void   main       (){
    int64 myRes
    int64 v1
    int64 v2
    myRes <- myF(2)
    v1 <- myRes * 3
    v2 <- myRes + v1
    return v2
}
int64   myF      (int64 p1){
   int64 p1
   int64 p2
   p2 <- p1 + 1
   return p2
}
```

LA standard library

- int64 input (void)
- void print (int64)
- void print (int64[])
- void print (int64[][])
- …

LA standard library

- int64 input (void)
- void print (int64([])*)
- void print (tuple)

No tensor-error

IR

```
define int64 @test (){
   :entry
   int64 %myRes
   int64 %v1
   int64 %v2
   %myRes <- call @myF(5)
   %v1 <- %myRes * 7
   %v2 <- %myRes + %v1
   return %v2 }
define int64 @myF (int64 %p1){
  :myLabel
  int64 %p1
  int64 %p2
  %p2 <- %p1 + 3
  return %p2 }
```

LA

```
int64 test (){
   int64 myRes
   int64 v1
   int64 v2
   myRes <- myF(2)
   v1 <- myRes * 3
   v2 <- myRes + v1
   return v2
}
int64 myF (int64 p1){
  int64 p1
  int64 p2
  p2 <- p1 + 1
  return p2
}
```

LA and invalid memory acccess

```
int64 test (){
   int64[] v
   v <- new Array(2)
   int64 s
   s <- v[100] ←
   return 0
}
```

LA and variable definitions

- LA variables must be defined before being used

- The scope of LA’s variables is the function
  - They can be defined anywhere in the function
  - There is no semantic difference between defining a variable in the middle of the function and defining it at the beginning of that function

Final notes

- Implicit return instruction if missing
- LA integer variables are implicitly initialized to zero of the LA language
    - One in IR, L3, L2, L1, x86_64
- LA code variables are initialized to 0
    - Reading a 0 in a code variable is a bug
- Having all variables implicitly initialized and having made impossible invalid memory access leaves integer overflow as the **only** other undefined behavior

```
int64 test (){
   int64 v
   print(v)
}
```

Now that you know LA, rewrite your IR programs in LA

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Value encoding

- Values in LA **are not** encoded
- Values in IR
  (beside array/tuple indices, and the 2nd parameter of length)
  are encoded
- The LA compiler needs to encode the values
  - Solution 1: (this class)
    - Everything is encoded
    - When needed, decode just before uses
  - Solution 2: (advanced)
    - Everything is decoded
    - Encode just before invoking the runtime

Value encoding example

LA

```
int64 v1

…

br v1 :L1 :L2

…
```

IR

```
in64 %v1

int64 %v1_new

%v1 <- 1

…

%v1_new <- v1 >> 1

br %v1_new :L1 :L2

…
```

Integer variables are initialized to “zero”, which encoded is 1

Value encoding example 2

LA

```
Int64[] v1

…

br v1 :L1 :L2

…
```

IR

```
In64[] %v1

…

br %v1 :L1 :L2

…
```

Value encoding example 3

LA

```
int64 v1
int64 v2
int64 v3
…
v3 <- v1 + v2
…
```

IR

```
int64 %v1
int64 %v2
int64 %v3
int64 %v1_new
int64 %v2_new
…
%v1_new <- %v1 >> 1
%v2_new <- %v2 >> 1
%v3 <- %v1_new + %v2_new
%v3 <- %v3 << 1
%v3 <- %v3 + 1
…
```

Value encoding: toDecode(i)

1. toDecode(br t label label) = t
2. toDecode(var1 <- length var2 var3) = var3
3. toDecode(var1 <- var2([vari])$^+$) = ([vari])$^+$
4. toDecode(var1([vari])$^+$ <- s) = ([vari])$^+$
5. toDecode(var <- t1 op t2) = t1, t2
6. toDecode(everything else) =

Value encoding: toEncode(i)

1. toEncode(var <- t op t) = var
2. toEncode(everything else) =

Value encoding algorithm

1. Encode all constants not used for array/tuple indices and 2nd parameter of length
2. For each instruction *i*
    A. For every variable or number *t* in toDecode(i)
        I. Create a new variable *v′*
        and place its definition to the first basic block
        II. Store the decoded value of *t* in *v′*
        III. Change *i* to use *v′* instead of *t*
    B. For every variable *v* in toEncode(i)
        I. Encode *v* just after *i*

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LA

```
p      ::= f+
f      ::=     T name ( (type name)* ) { i* }
i      ::= type name | name <- t | name <- t op t |
           label | br label  | br t label label | return | return t
           name <- name([t])+ | name([t])+ <- t |
           name <- length name t |
           name( args? ) | name <- name( args? ) |
           name <- new Array(args) | name <- new Tuple(t)
T      ::= type | void
type   ::= int64([])* | tuple | code
args   ::= t | t (, t)*
t      ::= name | N
N      ::= (+|-)? [0-9]+
op     ::= + | - | * | & | << | >> | < | <= | = | >= | >
name ::= [a-zA-Z_][a-zA-Z_0-9]*
label  ::= :name
```

Checking array/tuple accesses

To avoid invalid memory accesses, we need to generate code to

1. Check if an array or tuple has been allocated before their use

2. Check if the indexes used to access an array are within the allowed ranges

Checking array/tuple allocation

To check if an array or tuple has been allocated before their use

1. Initialize an array/tuple variable to 0 at their declaration

2. Before every array/tuple access:
    1. Check if the array/tuple variable v is not 0
    2. If it is 0, then call tensor-error(int64 line) passing the line number of the LA file of the incorrect instruction

Checking allocation example

LA

```
   int64[] v1
41 …
42 v3 <- v1[0]
43
```

```
static void apply( const Input & in,
                   Program & p){
  auto ln = in.position().line;
}
```

Line numbers of the LA file

IR

```
int64 %LineNumber
in64[] %v1
%v1 <- 0
…
%LineNumber <- 42
int64 %newV
%newV <- %v1 = 0
br %newV :ERROR :CORRECT
:ERROR
tensor-error(%LineNumber)
:CORRECT
…
%v3 <- %v1[0]
```

Checking allocation example

LA

```
   int64[] v1

41 …
42 v3 <- v1[0]
43
```

Line numbers of the LA file

IR

```
int64 %LineNumber
in64[] %v1
%v1 <- 0
…
%LineNumber <- 42
int64 %newV
%newV <- %v1 = 0
br %newV :F :C
:F
tensor-error(%LineNumber)
:C
…
%v3 <- %v1[0]
```

Checking whether the memory has been allocated or not

Checking allocation example

LA

```
    Int64[] v1

41  …
42  v3 <- v1[0]
43
```

Line numbers of the LA file

IR

```
int64 %LineNumber
in64[] %v1
%v1 <- 0
…
%LineNumber <- 42
int64 %newV
%newV <- %v1 = 0
br %newV :F :C
:F
tensor-error(%LineNumber)
:C
…
%v3 <- %v1[0]
```

Error reporting

Checking whether the memory has been allocated or not

Checking allocation example

LA

```
   Int64[] v1

41 …
42 v3 <- v1[0]
43
```

Line numbers of the LA file

IR

```
int64 %LineNumber
in64[] %v1
%v1 <- 0
…
%LineNumber <- 42
int64 %newV
%newV <- %v1 = 0
br %newV :F :C
:F
tensor-error(%LineNumber)
:C
…
%v3 <- %v1[0]
```

Error reporting

Checking whether the memory has been allocated or not

Checking whether the memory offset is within the object allocated

Checking single-dimension array accesses

Check if the index used to access a single-dimension array are within the allowed range

1. Before every array access
   (and hence after the above check)
   - A. For the index i used (e.g., ar[i])
     - I. Load the length of the relative dimension
       (e.g., l_i <- length ar 0)
     - II. Check if i is less than that length
       (e.g., i < l_i)
     - III. If it isn't, then call
       tensor-error(int64 line, int64 length, int64 index)

Length of the array allocated

You can assume indexes are not negative

Checking tensor acesses

Check if the indexes used to access a tensor are within the allowed ranges

1. Before every tensor access (and hence after the above check)
    - A. For every index i (e.g., t[k][i][j])
        - I. Load the length of the relative dimension (e.g., l_i <- length t 1)
        - II. Check if i is less than that length (e.g., i < l_i)
        - III. If it isn't, then call tensor-error(int64 line, int64 d, int64 length, int64 index)

First dimension (from left to right) of the tensor incorrectly accessed

Length of the dimension incorrectly accessed

Index used to access this dimension

You can assume indexes are not negative

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Instructions without basic blocks

Instructions organized in basic blocks

```
Inst = F.entryPoint() ; newInsts = new List() ; startBB = true ;
While (Inst){
  if (startBB){   // Next instruction must be a label
     if (Inst is not Label) {
         L = new Label() ; newInsts.append(L) ;
      }
     startBB = false;
  } else if (Inst is Label){  // L1 $i^+$ L2 ...
      g = new Goto(Inst); newInsts.append(g) ; // L1 $i^+$ goto L2 ...
  }
  newInsts.append(Inst) ;
  if (Inst is Terminator) { // Next instruction must be a label
      startBB = true;
  }
  Inst = F.nextInst(Inst);
}
...
```

See next slide

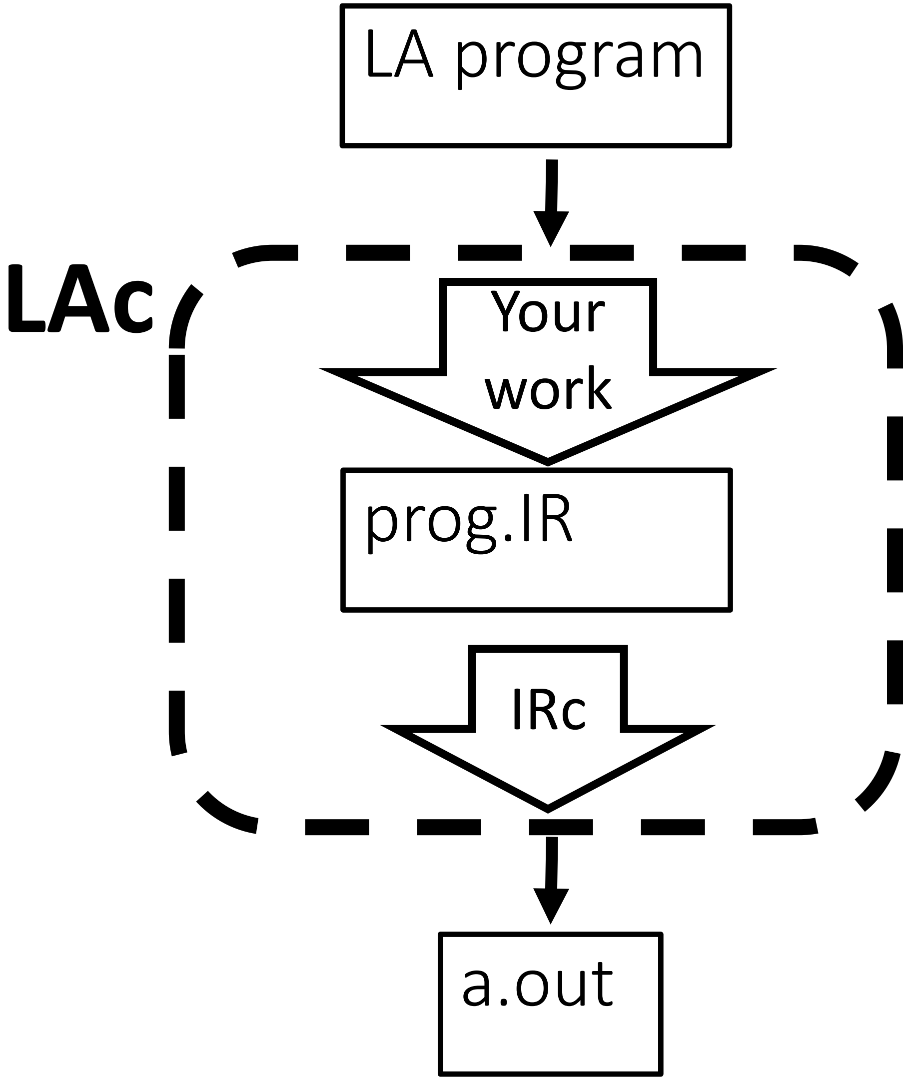
Previous slide

```
...
If (!startBB){
  if (Function’s return type is void){
    r = new Return()
  } else {
    r = new Return(0)
  }
  newInsts.append(r)
}
```

Variable definitions

- Collect all LA variable definitions
- Generate IR variable definitions (in any order) at the beginning of the first basic block
- Append to the first basic block the initialization of code variables to `0`

The LA compiler (LAc)



- To build LAc:
  translate an LA program
  to an equivalent IR one

- We need to
  - Encode values
  - Generate code to check memory accesses
  - Create basic blocks

Homework #6

Write a compiler that translates an LA program (.a) to an IR one

- You need to generate prog.IR
- You need to pass all tests in the framework

Always have faith in your ability

Success will come your way eventually

Best of luck!