CSE443
Compilers

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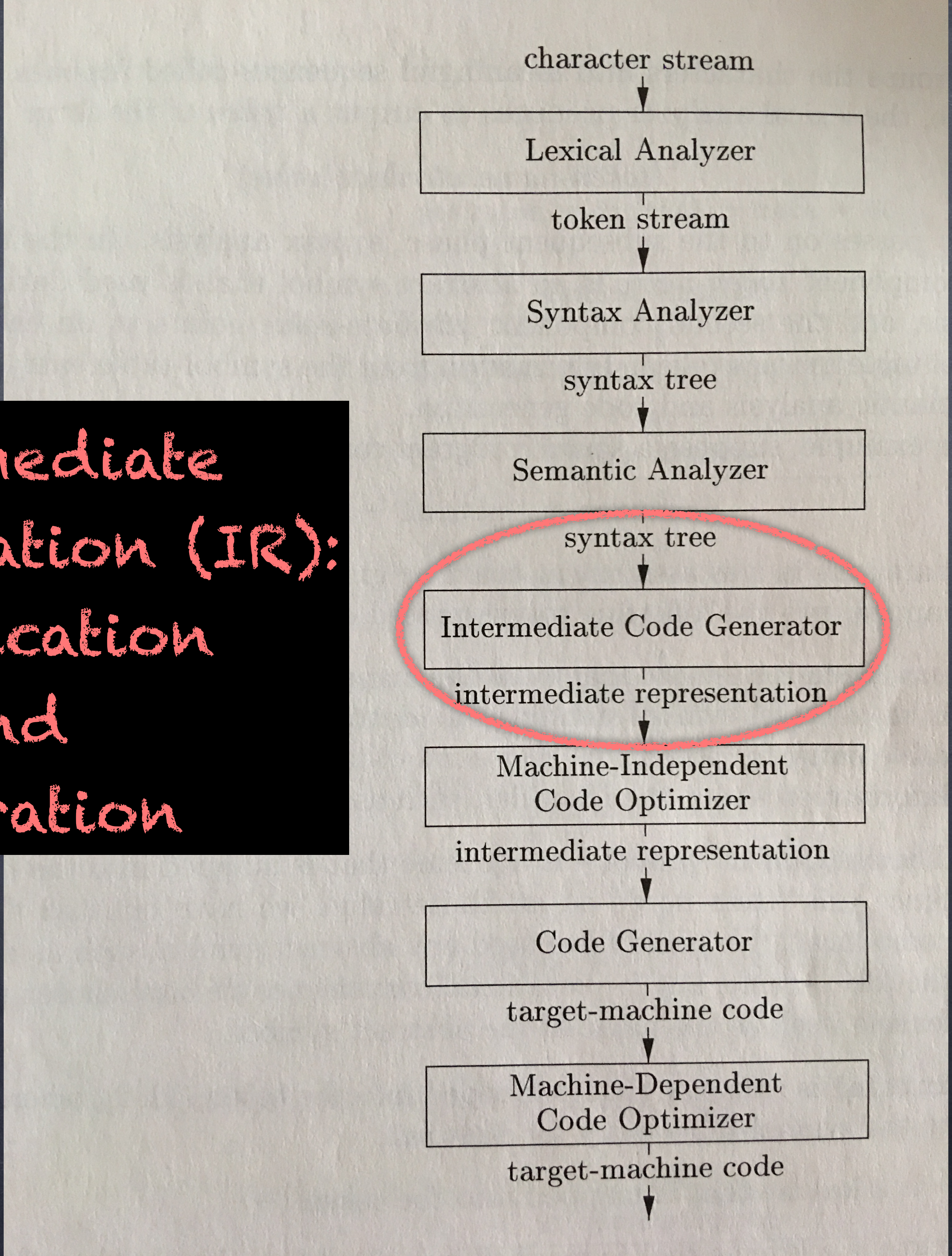
Phases of a compiler

Intermediate Representation (IR): specification and generation



character stream

Lexical Analyzer

token stream

Syntax Analyzer

syntax tree

Semantic Analyzer

syntax tree

Intermediate Code Generator

intermediate representation

Machine-Independent Code Optimizer

intermediate representation

Code Generator

target-machine code

Machine-Dependent Code Optimizer

target-machine code

Figure 1.6, page 5 of text

Scopes

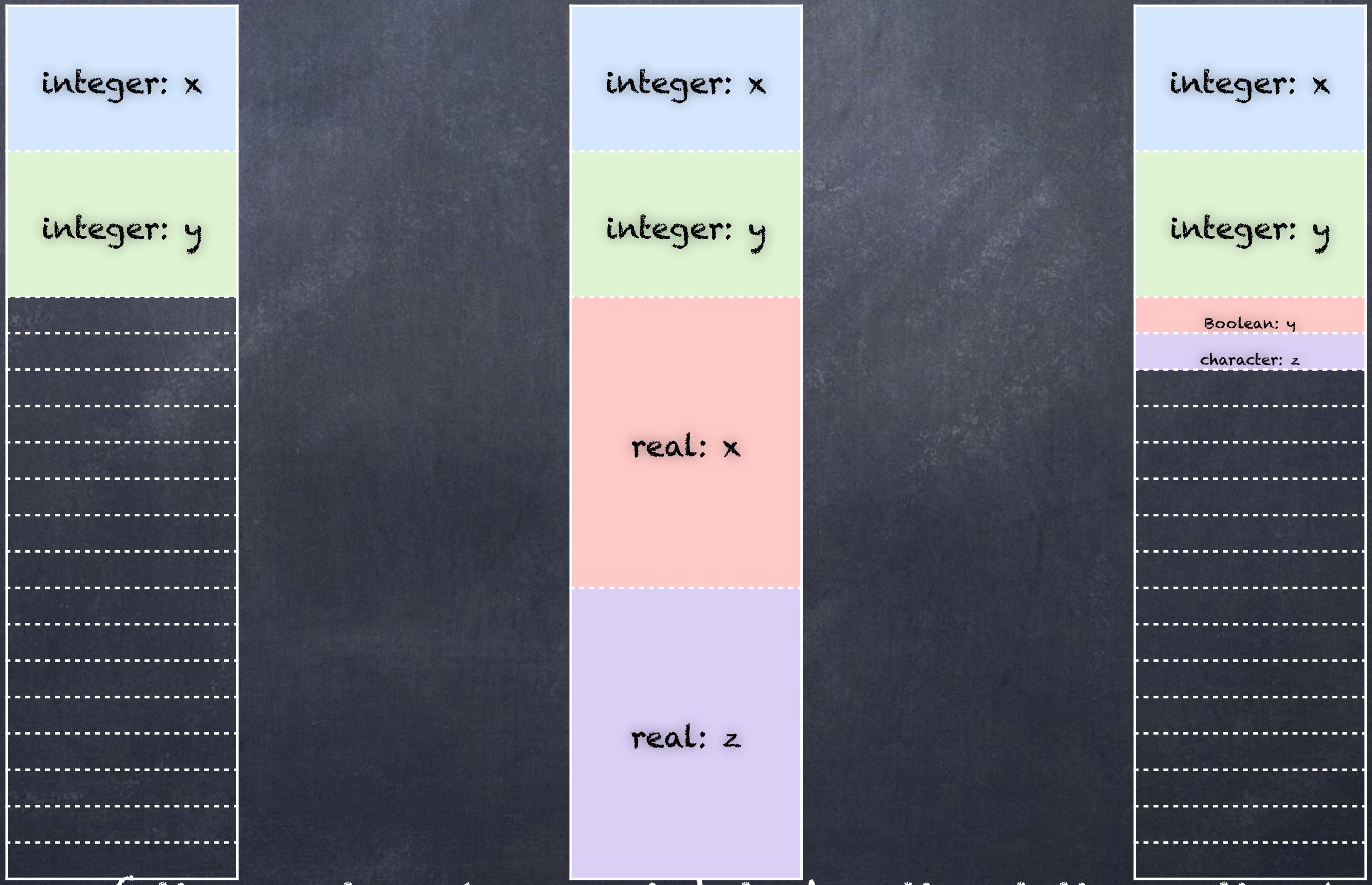
dblocks (6.3.5 and 6.3.6)

records (in separate symbol table), sequence of declarations at start of sblock

```
dblock -> '['
          { Stack.push(offset); }
          declaration-list ']'
          { offset=Stack.pop(); }
```

Since declarations must be gathered together at the start of an sblock, and cannot themselves be directly nested: keep running offset, but remember old offset when entering embedded scope.

```
offset = 0             offset = 4  offset = 8
{ [ integer :        x          ,  y    ]
push offset = 8 onto stack
        offset = 8        offset = 16   offset = 24
      { [ real :       x              ,  z     ] … … }
pop offset = 8  from stack
push offset = 8 onto stack
       offset = 8              offset = 9                      offset = 10
     { [ Boolean :          y              ; character : z          ]
          … …
     }
pop offset = 8  from stack
  }
```



dblocks (6.3.5 and 6.3.6)

records (in separate symbol table), sequence of declarations at start of sblock

Since declarations must be gathered together at the start of an sblock, and cannot themselves be directly nested, we can do better:

```
dblock → '['
        { ~~Env.push(st); st = new Env();~~ Stack.push(offset); ~~offset = 0;~~ }
        declaration-list ']'
        { ~~dblock.type=record(st); dblock.width=offset; st=Env.pop();~~ offset=Stack.pop(); }
```

```
  offset = 0          offset = 4   offset = 8
{ ( integer :       x            , y          )
push offset = 8 onto stack
      offset = 8     offset = 16  offset = 24
    { ( real :     x ,          z )  … … }
pop offset = 8  from stack
push offset = 8 onto stack
      offset = 8        offset = 9         offset = 10
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      … …
    }
pop offset = 8  from stack
  }
```

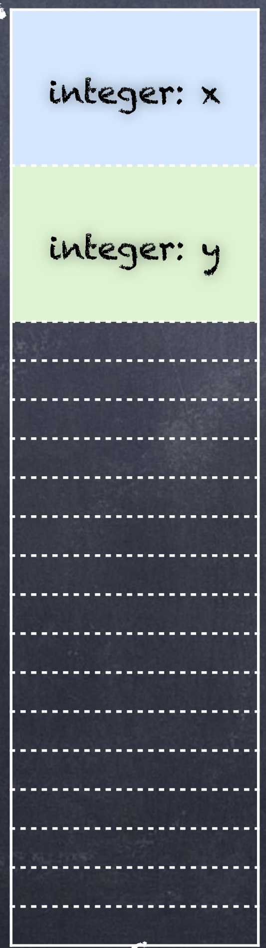

AT RUNTIME

dblocks (6.3.5 and 6.3.6)

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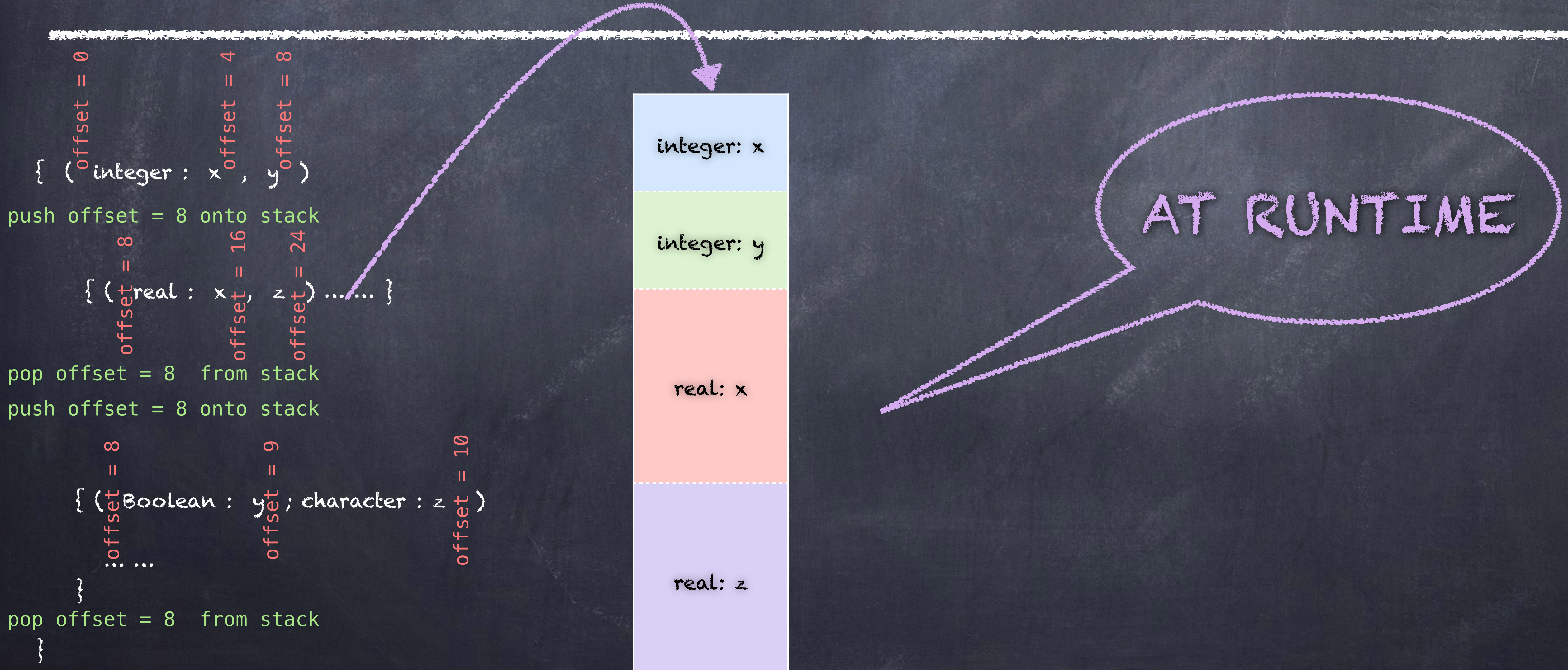

offset = 0 offset = 4 offset = 8

{ (integer : x , y)

push offset = 8 onto stack

offset = 8 offset = 16 offset = 24

{ (real : x , z) …… }

pop offset = 8 from stack

push offset = 8 onto stack

offset = 8 offset = 9 offset = 10

{ (Boolean : y ; character : z)

… …

}

pop offset = 8 from stack

}

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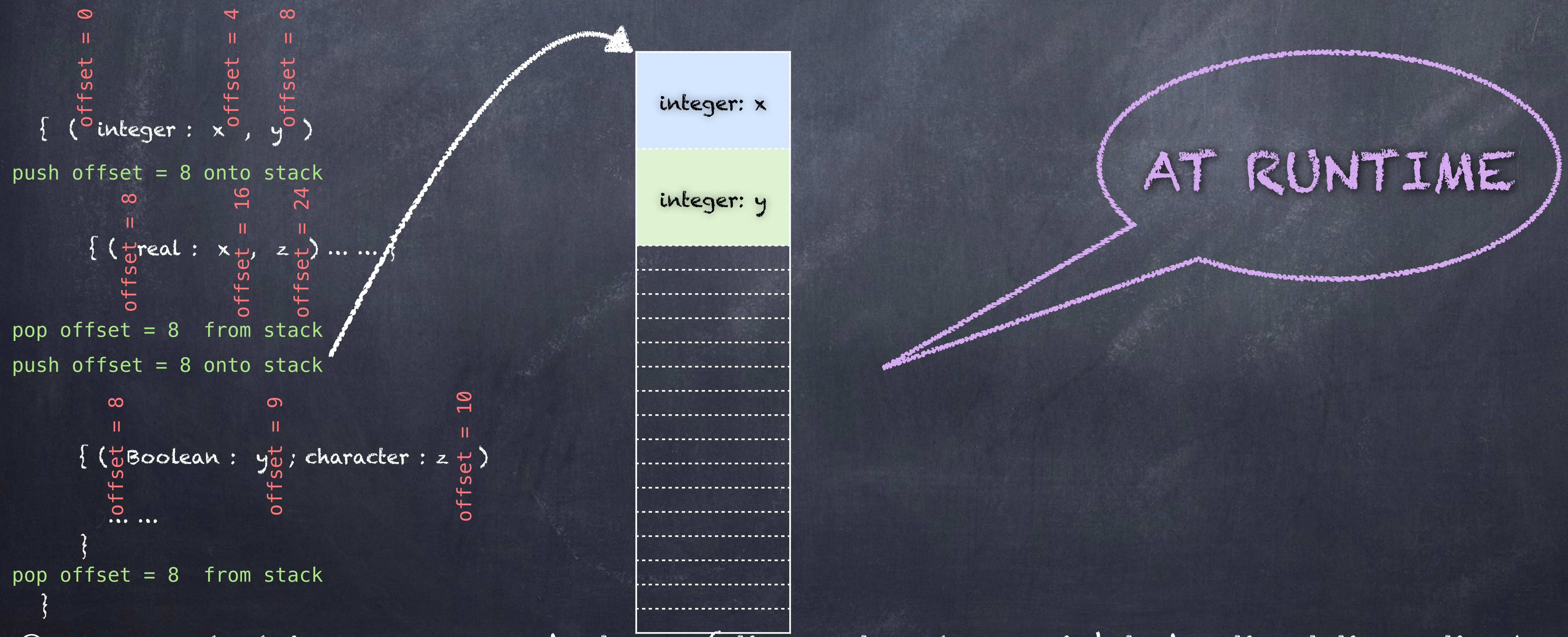

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push offset = 8 onto stack
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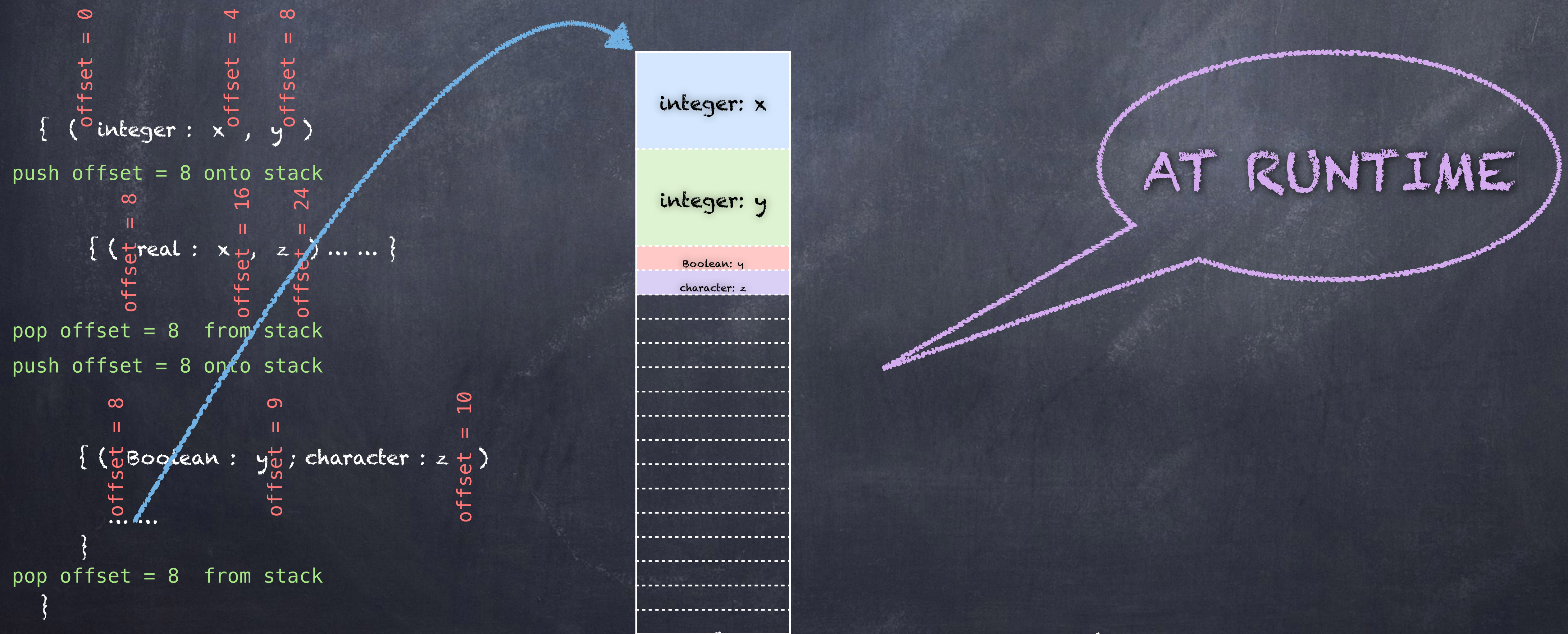

```
{ (integer : x, y)
push offset = 8 onto stack
    { (real : x, z) … … }
pop offset = 8  from stack
push offset = 8 onto stack
    { (Boolean : y; character : z)
    ……
    }
pop offset = 8  from stack
}
```

dblocks (6.3.5 and 6.3.6)

records (in separate symbol table), sequence of declarations at start of sblock

Since declarations must be gathered together at the start of an sblock, and cannot themselves be directly nested, we can do better:

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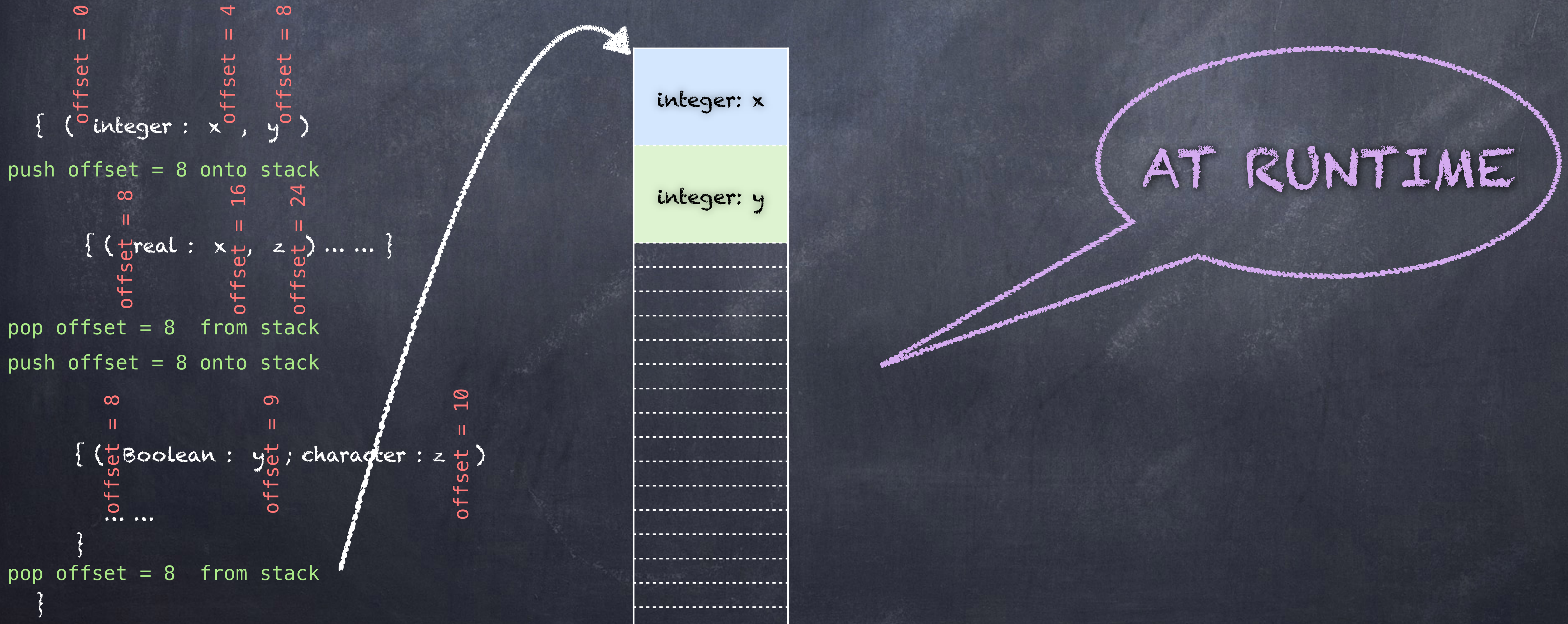

```
{ ( integer : x , y )
push offset = 8 onto stack
    { ( real : x , z ) … … }
pop offset = 8  from stack
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      … …
    }
pop offset = 8  from stack
}
```

Dealing with alignment

"On many machines, instructions [...] may expect integers to be aligned, that is, placed at an address divisible by 4" [p. 428]

Dealing with alignment

```
{  [ Boolean : a ; integer :  x  ; character c ; real : y ]

   { [ character : d ; integer :  r , s ] ... }

   { [ Boolean : f , g ; real : t ; character h ] ... }

}
```

"On many machines, instructions [...] may expect integers to be aligned, that is, placed at an address divisible by 4" [p. 428]

Dealing with alignment

```
{ [ Boolean : a ; integer :  x  ; character c; real : y ]

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  { [ Boolean : f , g ; real : t ; character h ] ... }

}
```

"On many machines, instructions [...] may expect integers to be aligned, that is, placed at an address divisible by 4" [p. 428]

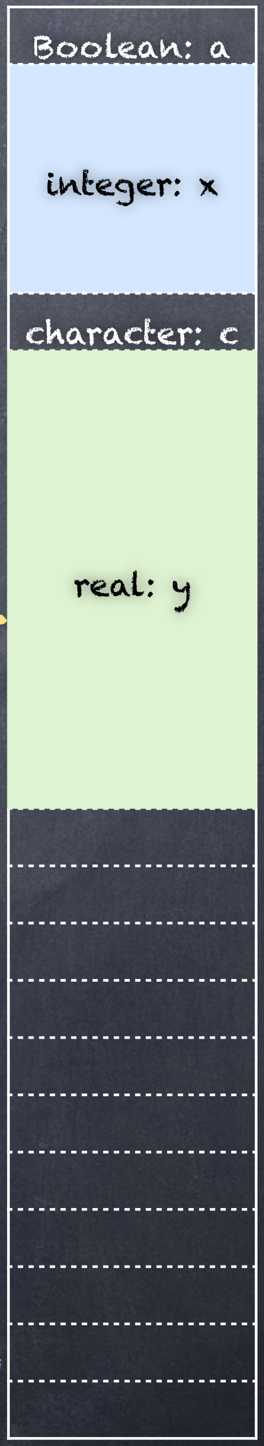
Dealing with alignment

```
{  [ Boolean : a ; integer :  x  ; character c; real : y ]

   { [ character : d ; integer :  r , s ] ... }

   { [ Boolean : f , g ; real : t ; character h ] ... }

}
```

"On many machines, instructions [...] may expect integers to be aligned, that is, placed at an address divisible by 4" [p. 428]

Blocks are not aligned.

A block of size N bytes typically needs be aligned to an address divisible by N, where N is an integral power of 2 (1, 2, 4, 8)



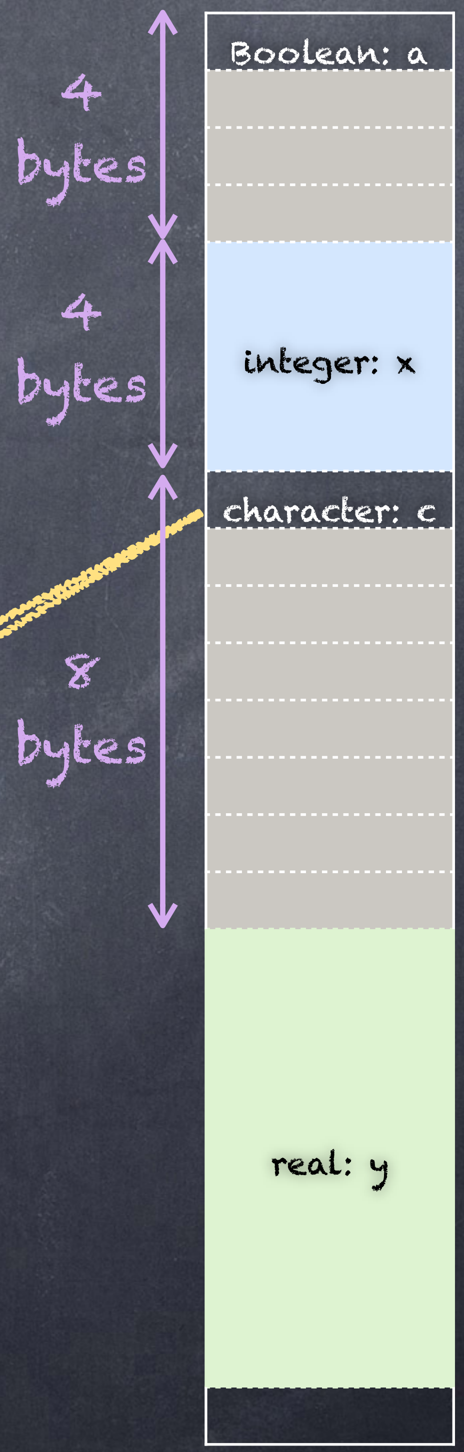
Dealing with alignment

{ [Boolean : a ; integer : x ; character c; real : y]

{ [character : d ; integer : r , s] … }

{ [Boolean : f , g ; real : t ; character h] … }

}

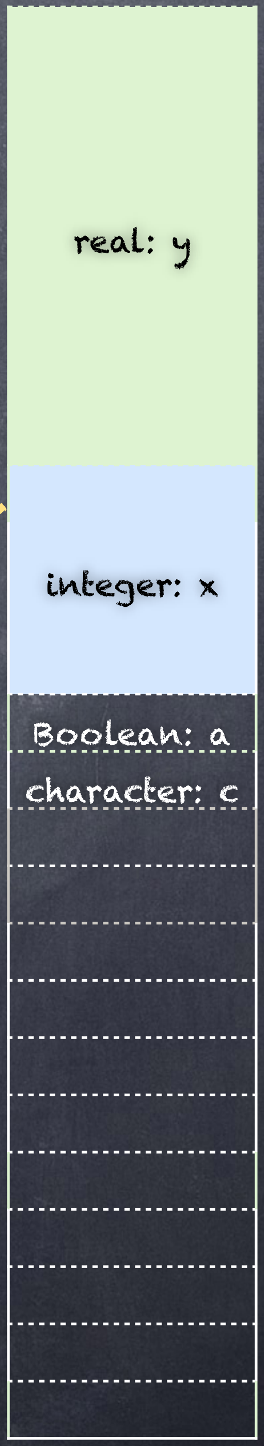


Blocks are aligned, but memory wasted to padding.

C will lay fields out in the order listed in the struct declaration.

Dealing with alignment

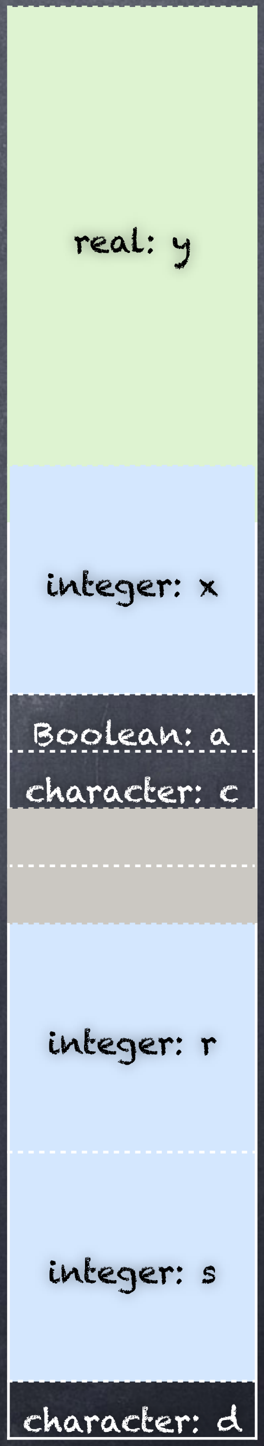
```
{  [ Boolean : a ; integer :  x  ; character c; real : y ]

   { [ character : d ; integer :  r , s ] ... }

   { [ Boolean : f , g ; real : t ; character h ] ... }

}
```



Blocks are aligned, no padding needed here.

Dealing with alignment

```
{  [ Boolean : a ; integer :  x  ; character c; real : y ]

   { [ character : d ; integer :  r , s ] ... }

   { [ Boolean : f , g ; real : t ; character h ] ... }

}
```



Blocks are aligned, padding needed before embedded scope block.

Offsets and alignment in the project

- The offsets for each variable in a scope is stored in its symbol table entry.
- The offsets must respect alignment constraints.
  - assume real is aligned to an 8-byte address boundary
  - assume int is aligned to a 4-byte boundary
  - assume smaller types can be at any address
  - assume reserve returns an address on an 8-byte boundary

Offsets and alignment in the project

- You may align using padding alone.
- You may align using a combination of re-organization of fields (large blocks before small blocks) and padding as necessary.
- Compute offsets during processing, and record in symbol table.

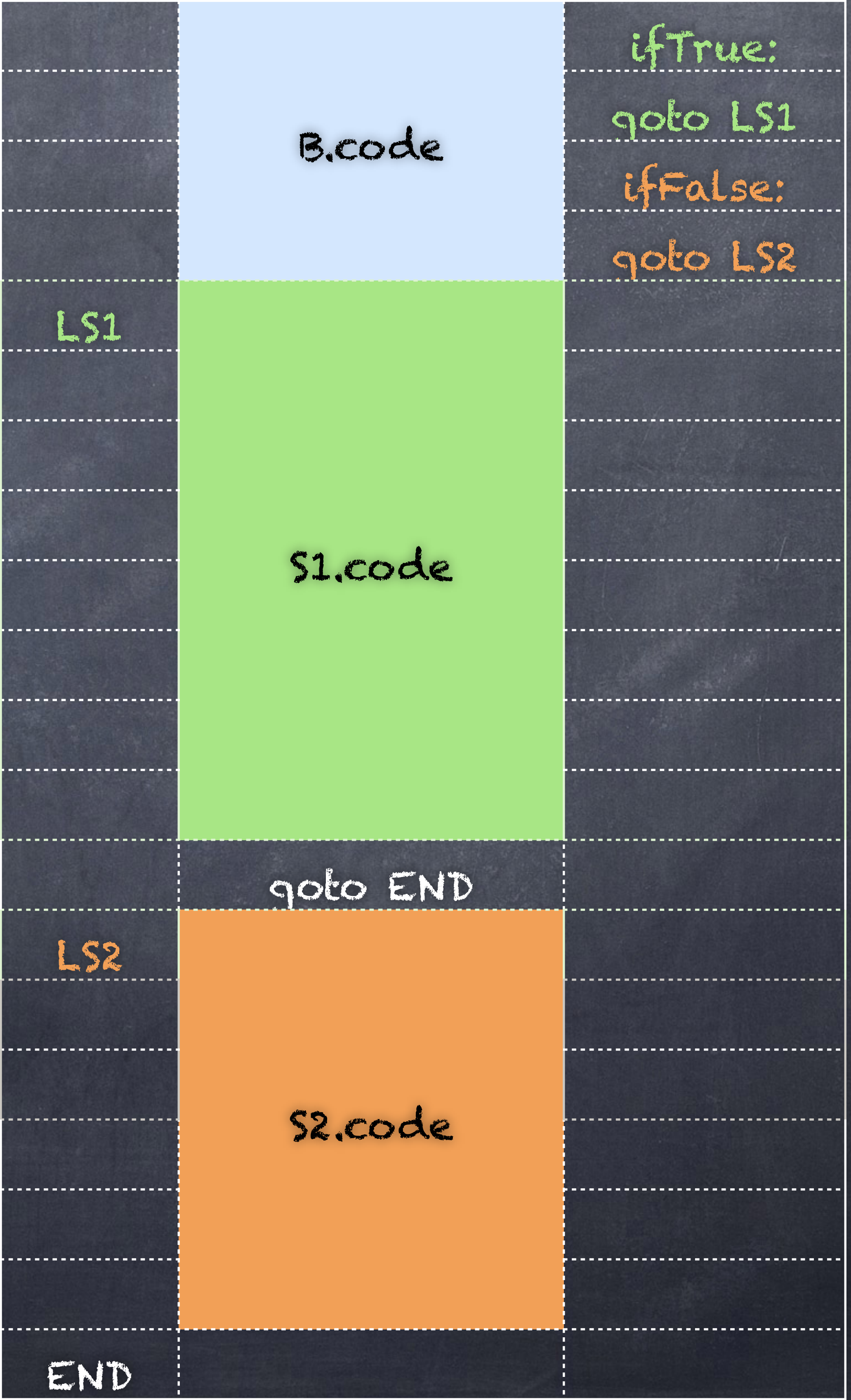
IR: a motivating example

Flow-of-Control (6.3.3)

if (B) then S1 else S2

Let's generalize from the previous concrete example to one with an arbitrary Boolean expression B.

We assume that IR instructions are placed into an array.



ifTrue:
goto LS1
ifFalse:
goto LS2

B.code

LS1

S1.code

goto END

LS2

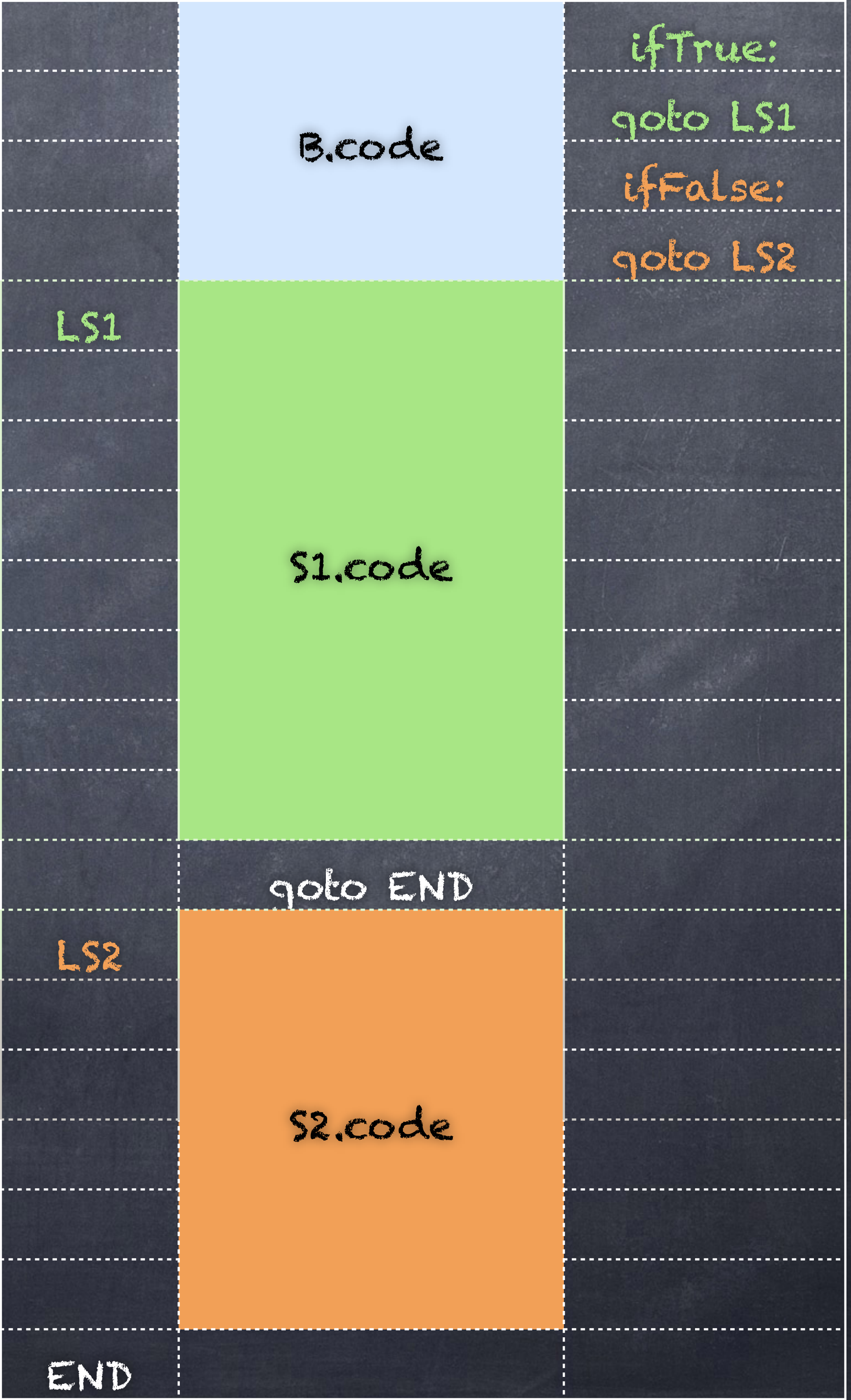
S2.code

END

Flow-of-Control (6.3.3)

if (B) then S1 else S2

```
B.true = newlabel()
B.false = newlabel()
S.next = S1.next = S2.next
S.code = B.code ||
label(B.true) || S1.code ||
gen('goto' S.next) ||
label(B.false) || S2.code
```



Flow-of-Control (6.3.3)

S -> if (B) then S1

B.true = newlabel()

B.false = S.next = S1.next

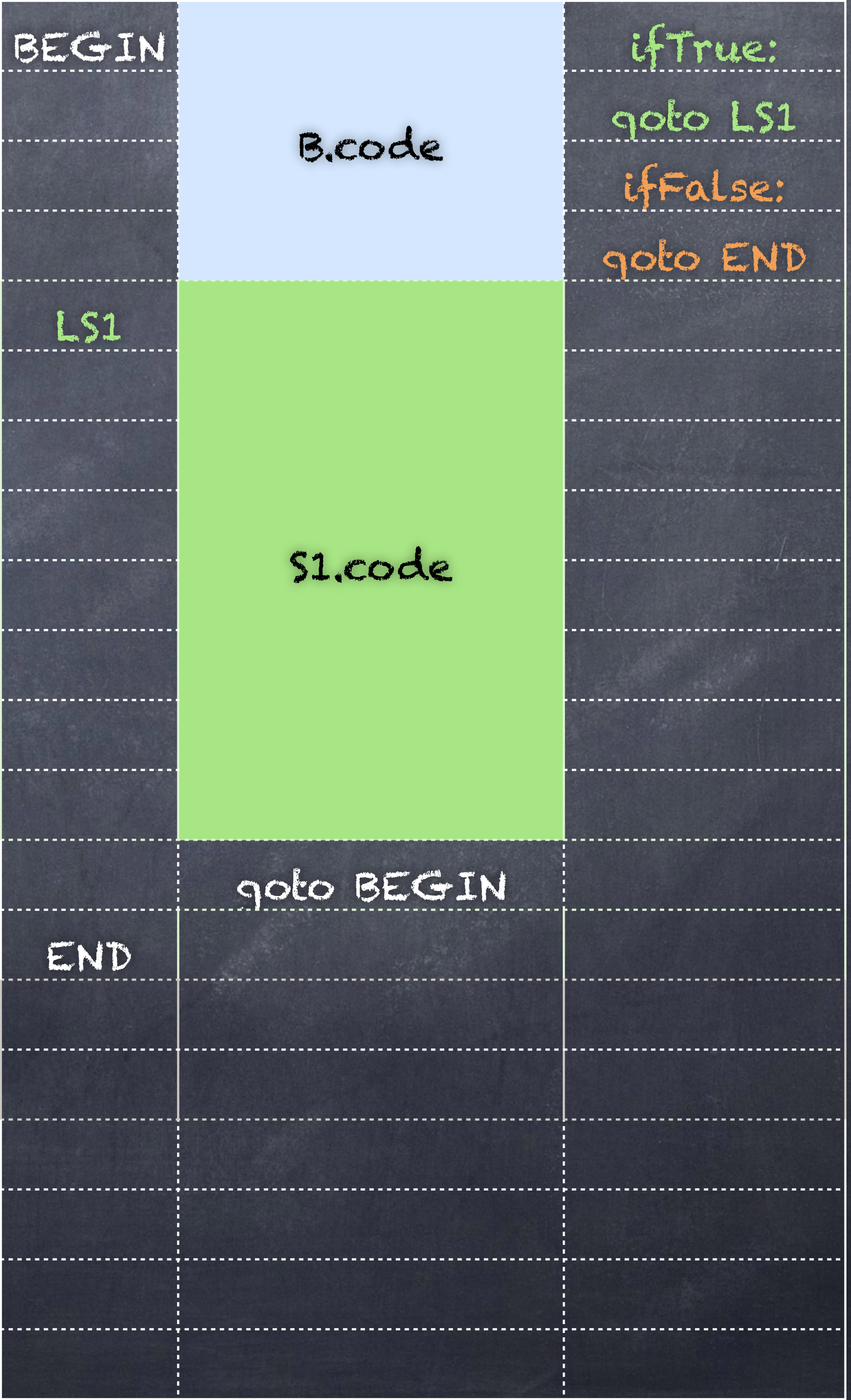
S.code = B.code ||

label(B.true) || S1.code

Flow-of-Control (6.3.3)

while (B) then S1

```
begin = newlabel()
B.true = newlabel()
B.false = S.next
S1.next = begin
S.code = label(begin) ||
B.code || label(B.true) ||
S1.code || gen('goto' begin)
```



Boolean expressions: value or control flow?

Boolean expressions

Boolean expressions can be evaluated

- to determine the flow of control
- for their value

6.6.6 Boolean values and jumping code

"S -> id = E; | if (E) S | while (E) S | S S

Nonterminal E governs the flow on control in S -> while (E) S1. The same nonterminal E denotes a value in S -> id = E; [...]"

[p. 408]

6.6.6 Boolean values and jumping code

"Suppose that attribute E.n denotes the syntax-tree node for an expression E and that nodes are objects. Let method jump generate jumping code at an expression node, and let method rvalue generate code to compute the value of the node into a temporary."

[p. 408]

Value of Boolean expression

"When E appears in S -> while (E) S1,
method jump is called at node E.n
[...]
When E appears in S -> id = E;, method
rvalue is called at node E.n" [p. 408]

Figure 6.42 [p. 409]

"If E has the form E1 + E2, the method call E.n.rvalue() generates code as discussed in section 6.4." [p. 408]

```
"E-> E1 + E2
    E.addr = new Temp()
    E.code = E1.code || E2.code || gen(E.addr '=' E1.addr '+' E2.addr)" [p. 379]
```

"If E has the form E1 && E2 we first generate jumping code for E and then assign true or false to a new temporary t at the true and false exits, respectively, from the jumping code." [p. 408]

Translation of: x = a<b && c<d

```
     ifFalse a < b goto L1
     ifFalse c < d goto L1
     t = true
     goto L2
L1:  t = false
L2:  x = t
```

Boolean expressions

- Examples: !X X & Y X | Y

Boolean expressions

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- We will do short-circuit evaluation

Boolean expressions

- Examples: ! X X & Y X | Y
- We will do short-circuit evaluation
- For example:

  if (X | (Y & Z)) then { A } else { B }

  is translated as

```
      if X goto LA
      ifFalse Y goto LB
      ifFalse Z goto LB
LA:   A
      goto END
LB:   B
END: (next instruction)
```

Boolean expressions

- A concrete exercise - how is this translated?
- if (r < s | (r = s & 0 < s)) then { A } else { B }

Boolean expressions

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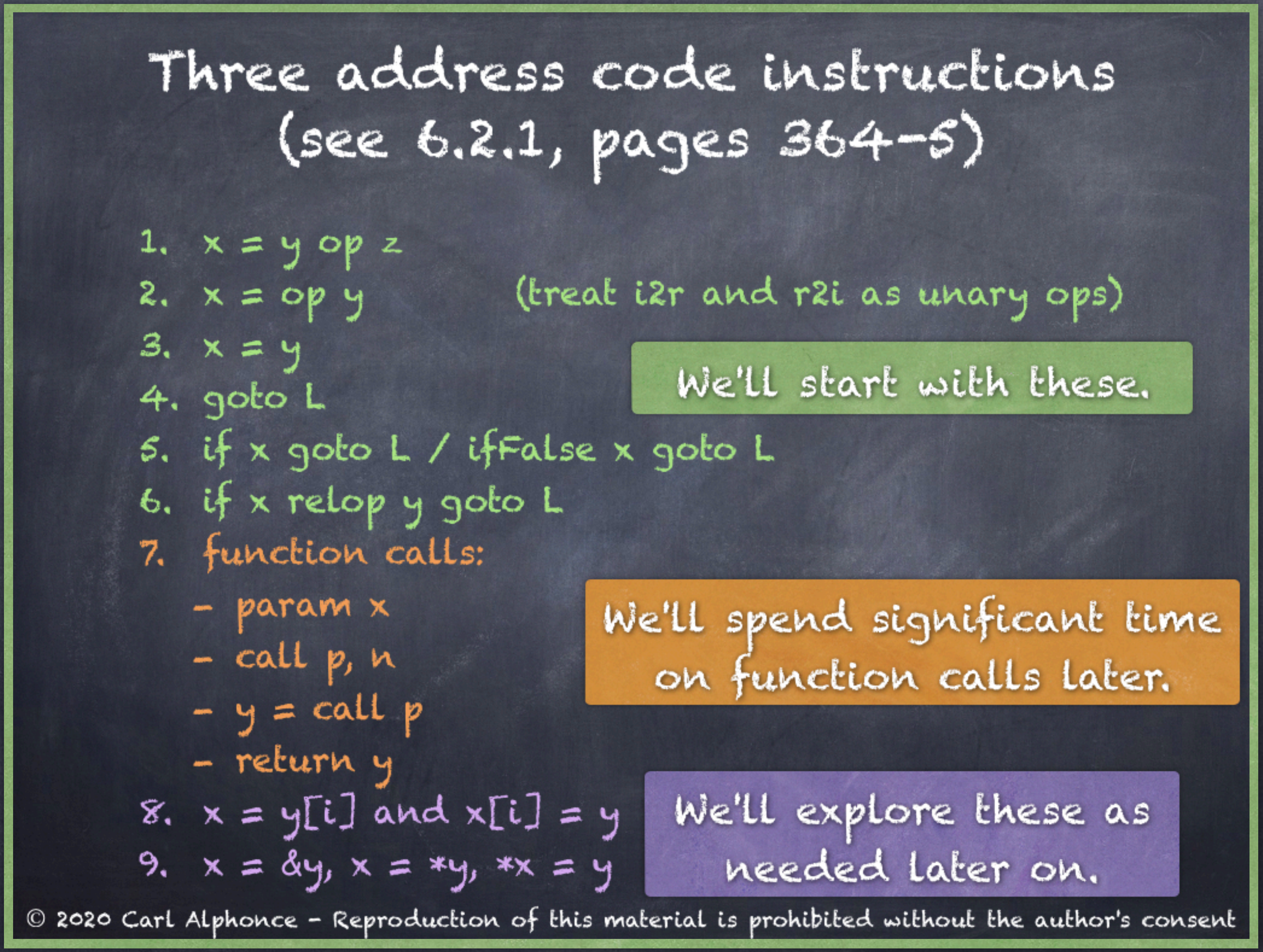
Here's a summary of the Intermediate Representation (IR) that we'll be using.



Three address code instructions (see 6.2.1, pages 364-5)

1. x = y op z
2. x = op y (treat i2r and r2i as unary ops)
3. x = y
4. goto L
5. if x goto L / ifFalse x goto L
6. if x relop y goto L
7. function calls:
   - param x
   - call p, n
   - y = call p
   - return y
8. x = y[i] and x[i] = y
9. x = &y, x = *y, *x = y

We'll start with these.

We'll spend significant time on function calls later.

We'll explore these as needed later on.

Boolean expressions

- A concrete exercise - how is this translated?
- if (r < s | (r = s & 0 < s)) then { A } else { B }

Exercise: try to come up with a suitable translation.

Three address code instructions (see 6.2.1, pages 364-5)

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Boolean expressions

- A concrete exercise - how is this translated?
- if (r < s | (r = s & 0 < s)) then { A } else { B }

This has the same form as our example:

if (X | (Y & Z)) then { A } else { B }
is translated as

```
     if X goto LA
     ifFalse Y goto LB
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LA:  A
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This has the same form as our example:

if (r<s | (Y & Z)) then { A } else { B } is translated as

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      if r<s goto LA
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Boolean expressions

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This has the same form as our example:

if (r<s | (r=s & 0<s)) then { A } else { B }
is translated as

```
     if r<s goto LA
     ifFalse r=s goto LB
     ifFalse 0<s goto LB
LA:  A
     goto END
LB:  B
END: (next instruction)
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Backpatching

Allows jump targets to be filled in during a one-pass parse.

When (forward) jumps are needed, keep a list of where the addresses need to be inserted.

Once address is known, go back and fill in the address ("backpatching").

6.7 Backpatching

"For specificity, we generate instructions into an instruction array, and labels will be indices into this array." [p. 410]

We have an instruction pointer (the first available index in the array), called nextinstr.

6.7 Backpatching

page 410

makelist(i) creates a new list containing only i, an index into the array of instructions; makelist returns a pointer to the newly created list.

merge(p1,p2) concatenates the lists pointed to by p1 and p2, and returns a pointer to the concatenated list.

backpatch(p,i) inserts i as the target label for each of the instructions on the list pointed to by p