Where In The Course Are We?

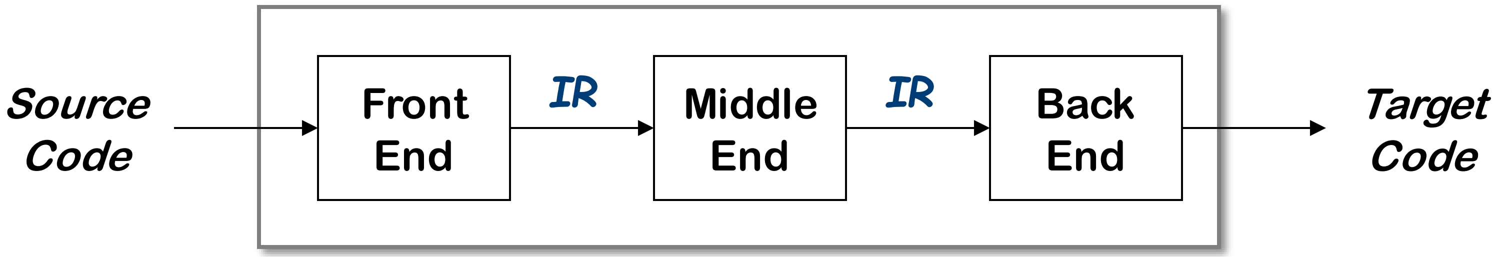
Obvious answer: at the start of Chapter 5 in EaC

More important answer

- We are on the cusp of the art, science, & engineering of compilation
- Scanning & parsing are applications of automata theory
- Context-sensitive analysis, as covered in class, is mostly software engineering
- The mid-section of the course will focus on issues where the compiler writer needs to choose among alternatives
  - The choices matter; they affect the quality of compiled code
  - There may be no "best answer" or "best practice"

To my mind, the fun begins at this point

Intermediate Representations



- Front end - produces an intermediate representation (*IR*)
- Middle end - transforms the *IR* into an equivalent *IR* that runs more efficiently
- Back end - transforms the *IR* into native code

- *IR* encodes the compiler's knowledge of the program
- Middle end usually consists of several passes

Intermediate Representations

- Decisions in *IR* design affect the speed and efficiency of the compiler
- Some important *IR* properties
  - Ease of generation
  - Ease of manipulation
  - Procedure size
  - Freedom of expression
  - Level of abstraction
- The importance of different properties varies between compilers
  - Selecting an appropriate *IR* for a compiler is critical

Types of Intermediate Representations

Three major categories

- Structural
  - Graphically oriented
  - Heavily used in source-to-source translators
  - Tend to be large
- Linear
  - Pseudo-code for an abstract machine
  - Level of abstraction varies
  - Simple, compact data structures
  - Easier to rearrange
- Hybrid
  - Combination of graphs and linear code
  - Example: control-flow graph

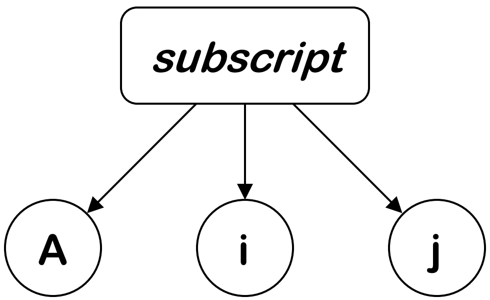
Examples:
Trees, DAGs

Examples:
3 address code
Stack machine code

Example:
Control-flow graph

Level of Abstraction

- The level of detail exposed in an *IR* influences the profitability and feasibility of different optimizations.
- Two different representations of an array reference:



loadI	1		=>	r_1
sub	r_j,	r_1	=>	r_2
loadI	10		=>	r_3
mult	r_2,	r_3	=>	r_4
sub	r_i,	r_1	=>	r_5
add	r_4,	r_5	=>	r_6
loadI	@A		=>	r_7
add	r_7,	r_6	=>	r_8
load	r_8		=>	r_{Aij}

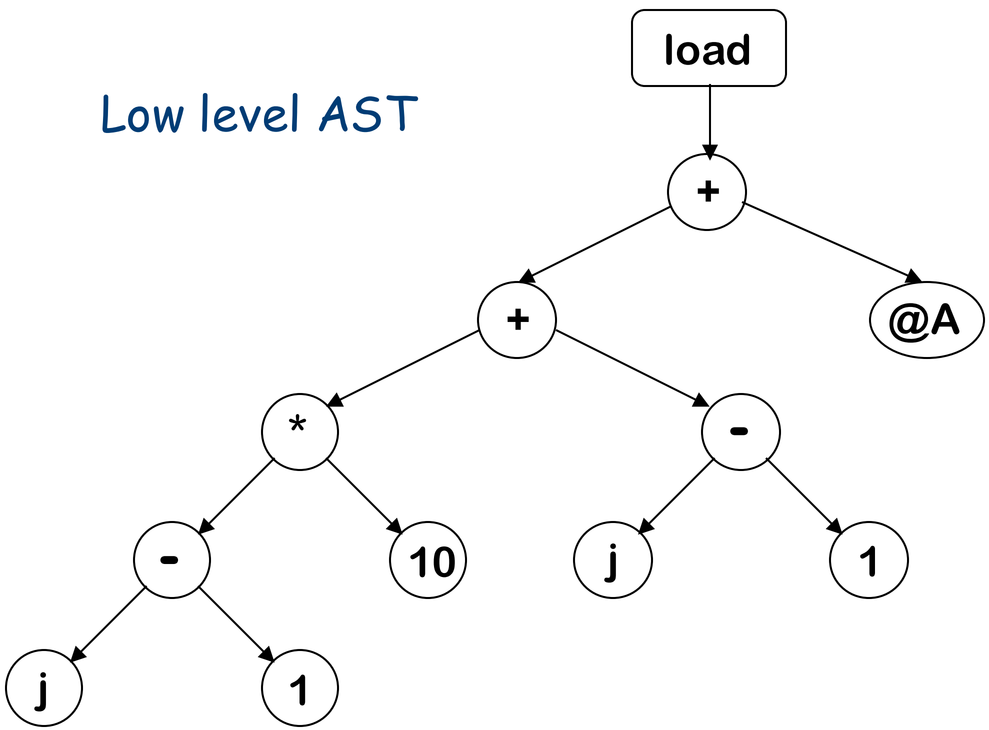
High level AST:
Good for memory disambiguation

Low level linear code:
Good for address calculation

Level of Abstraction

- Structural *IRs* are usually considered high-level
- Linear *IRs* are usually considered low-level
- Not necessarily true:

Low level AST



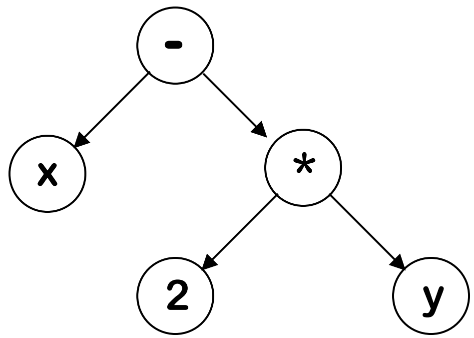

```
loadArray A,i,j
```

High level linear code

In Chapter 11 of EaC, we will see trees that have a lower level of abstraction than the machine code!

Abstract Syntax Tree

An abstract syntax tree is the procedure's parse tree with the nodes for most non-terminal nodes removed



x - 2 * y

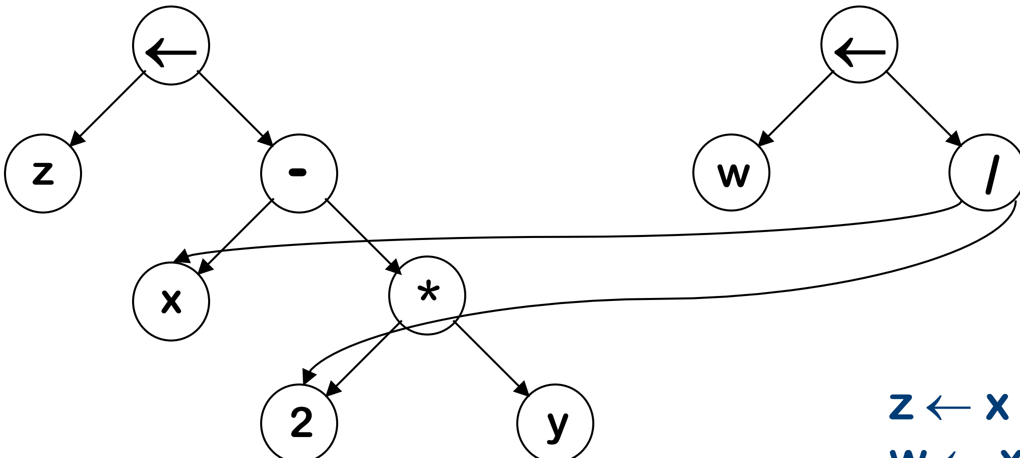
- Can use linearized form of the tree
  - Easier to manipulate than pointers

    `x 2 y * -` in postfix form

    `- * 2 y x` in prefix form
- S-expressions (Scheme,Lisp) are (essentially) ASTs

Directed Acyclic Graph

A directed acyclic graph (DAG) is an AST with a unique node for each value



$z \leftarrow x - 2 * y$
$w \leftarrow x \ / \ 2$

- Makes sharing explicit
- Encodes redundancy

With two copies of the same expression, the compiler might be able to arrange the code to evaluate it only once.

Stack Machine Code

Originally used for stack-based computers, now Java

- Example:

x - 2 * y becomes

```
push x
push 2
push y
multiply
subtract
```

Advantages

- Compact form
- Introduced names are *implicit*, not *explicit*
- Simple to generate and execute code

Implicit names take up no space, where explicit ones do!

Useful where code is transmitted over slow communication links (*the net*)

Three Address Code

Several different representations of three address code

- In general, three address code has statements of the form:

$$x \leftarrow y \ \underline{op} \ z$$

With 1 operator ($\underline{op}$) and, at most, 3 names (x, y, & z)

Example:

$z \leftarrow x - \boxed{2 * y}$ becomes

```
t ← 2 * y
z ← x - t
```

Advantages:

- Resembles many real machines
- Introduces a new set of names*
- Compact form

Three Address Code: Quadruples

Naïve representation of three address code

- Table of k * 4 small integers
- Simple record structure
- Easy to reorder
- Explicit names

The original FORTRAN compiler used "quads"

```
load   r1, y
loadI  r2, 2
mult   r3, r2, r1
load   r4, x
sub    r5, r4, r3
```

RISC assembly code

load	1	y	
loadi	2	2	
mult	3	2	1
load	4	x	
sub	5	4	3

Quadruples

Three Address Code: Triples

- Index used as implicit name
- 25% less space consumed than quads
- Much harder to reorder

(1)	`load`	`y`	
(2)	`loadI`	`2`	
(3)	`mult`	`(1)`	`(2)`
(4)	`load`	`x`	
(5)	`sub`	`(4)`	`(3)`

Implicit names occupy no space

Remember, for a long time, 640Kb was a lot of RAM

Three Address Code: Indirect Triples

- List first triple in each statement
- Implicit name space
- Uses more space than triples, but easier to reorder

Stmt List	Implicit Names	Indirect Triples		
(100)	(100)	load	y	
(105)	(101)	loadI	2	
	(102)	mult	(100)	(101)
	(103)	load	x	
	(104)	sub	(103)	(102)

- Major tradeoff between quads and triples is compactness versus ease of manipulation
  - In the past compile-time space was critical
  - Today, speed may be more important

Two Address Code

- Allows statements of the form

  $x \leftarrow x \; \underline{op} \; y$

  Has 1 operator ($\underline{op}$) and, at most, 2 names (x and y)

Example:

$z \leftarrow x - 2 * y$ becomes

```
t1 ← 2
t2 ← load y
t2 ← t2 * t1
z  ← load x
z  ← z - t2
```

- Can be very compact

Problems

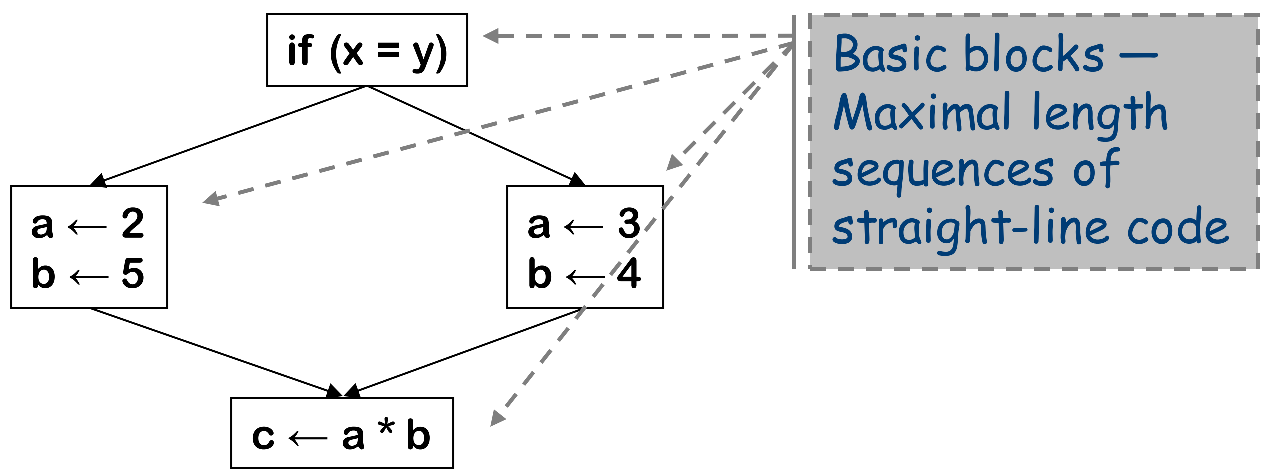
- Machines no longer rely on destructive operations
- Difficult name space
  - Destructive operations make reuse hard
  - Good model for machines with destructive ops (PDP-11)

Control-flow Graph

Models the transfer of control in the procedure

- Nodes in the graph are basic blocks
  - Can be represented with quads or any other linear representation
- Edges in the graph represent control flow

Example



Static Single Assignment Form

- The main idea: each name defined exactly once
- Introduce ϕ-functions to make it work

Original

```
x ← …
y ← …
while (x < k)
    x ← x + 1
    y ← y + x
```

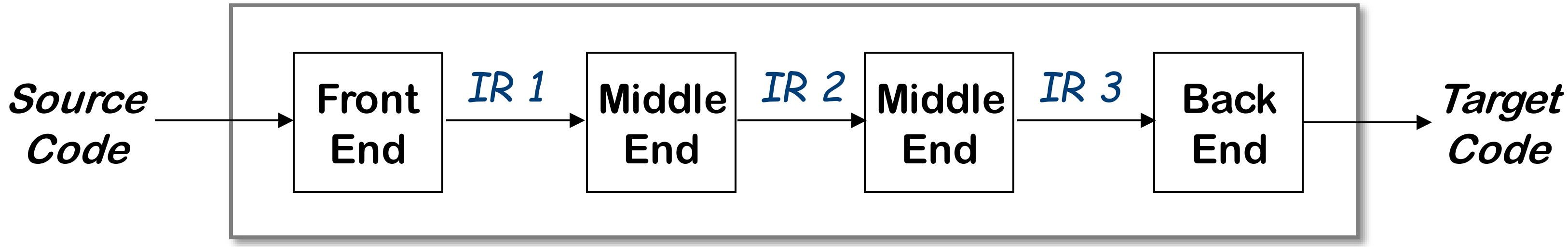
SSA-form

$$
\begin{array}{ll}
 & x_0 \leftarrow \ldots \\
 & y_0 \leftarrow \ldots \\
 & \text{if } (x_0 >= k) \text{ goto next} \\
\text{loop:} & \quad x_1 \leftarrow \phi(x_0, x_2) \\
 & \quad y_1 \leftarrow \phi(y_0, y_2) \\
 & \quad x_2 \leftarrow x_1 + 1 \\
 & \quad y_2 \leftarrow y_1 + x_2 \\
 & \quad \text{if } (x_2 < k) \text{ goto loop} \\
\text{next:} & \quad \ldots
\end{array}
$$

Strengths of SSA-form

- Sharper analysis
- ϕ-functions give hints about placement
- (sometimes) faster algorithms

Using Multiple Representations



- Repeatedly lower the level of the intermediate representation
  - Each intermediate representation is suited towards certain optimizations
- Example: the Open64 compiler
  - WHIRL intermediate format
    - → Consists of 5 different *IRs* that are progressively more detailed and less abstract

Memory Models

Two major models

- Register-to-register model
  - Keep all values that can legally be stored in a register in registers
  - Ignore machine limitations on number of registers
  - Compiler back-end must insert loads and stores
- Memory-to-memory model
  - Keep all values in memory
  - Only promote values to registers directly before they are used
  - Compiler back-end can remove loads and stores
- Compilers for RISC machines usually use register-to-register
  - Reflects programming model
  - Easier to determine when registers are used

The Rest of the Story…

Representing the code is only part of an *IR*

There are other necessary components

- Symbol table
- Constant table
  - Representation, type
  - Storage class, offset
- Storage map
  - Overall storage layout
  - Overlap information
  - Virtual register assignments

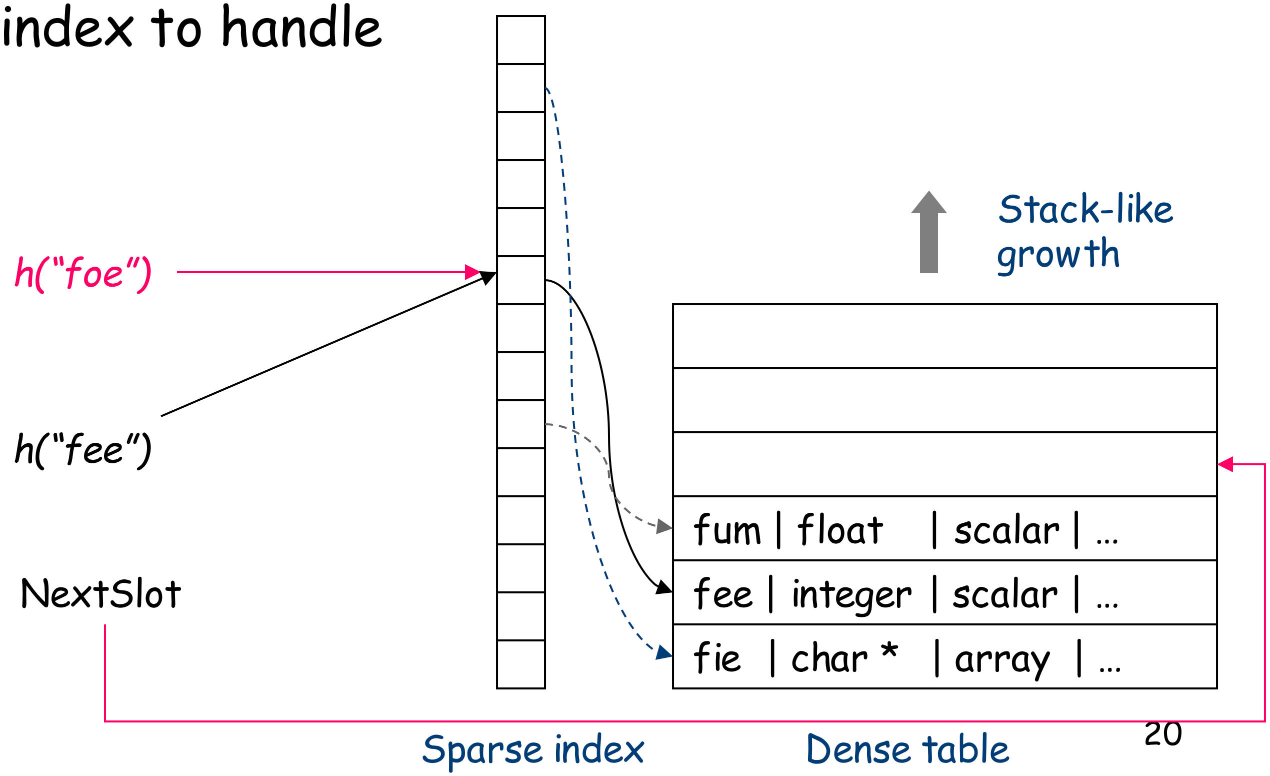
Symbol Tables

Classic approach to building a symbol table uses hashing

- Personal preference: a two-table scheme
  - Sparse index to reduce chance of collisions
  - Dense table to hold actual data
    - → Easy to expand, to traverse, to read & write from/to files
- Use chains in index to handle collisions

See § B.3 in EaC for a longer explanation

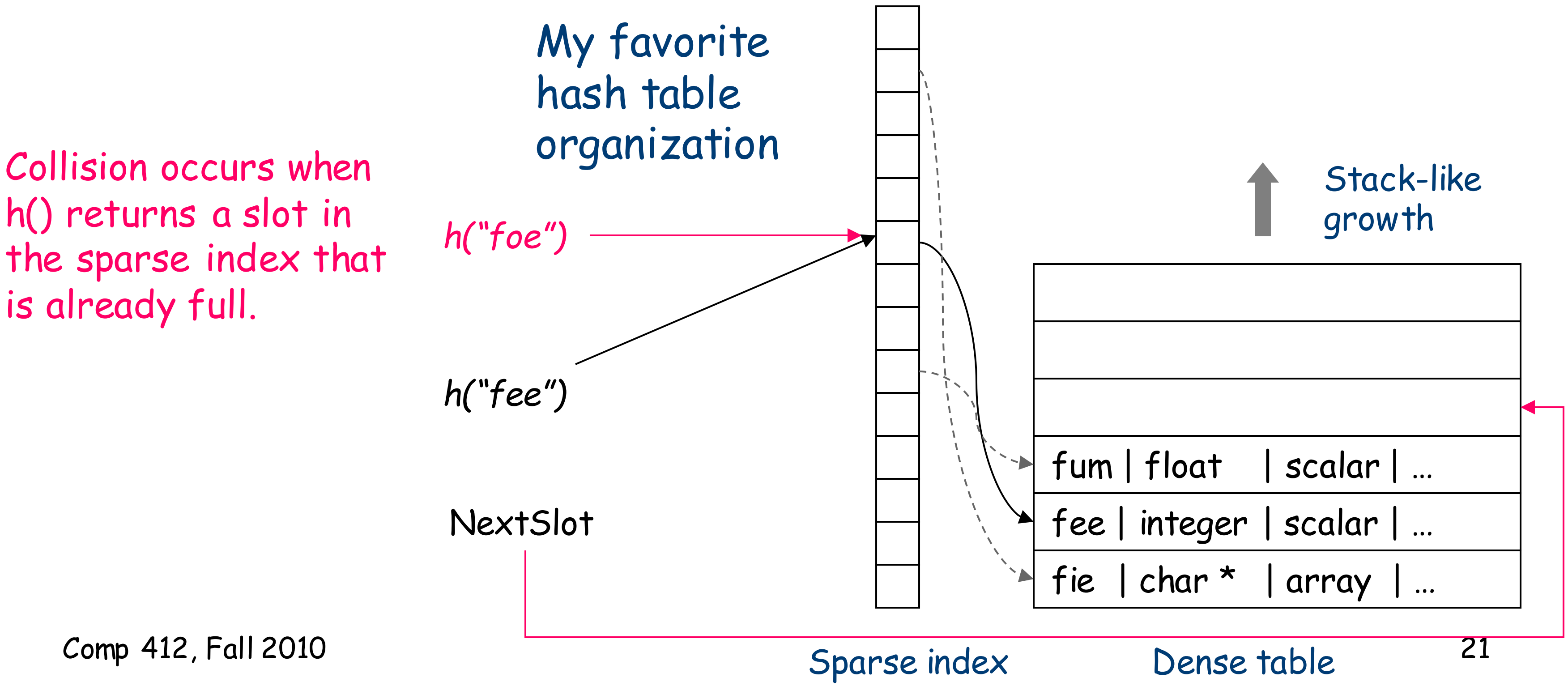
Collision occurs when h() returns a slot in the sparse index that is already full.



Hash-less Symbol Tables

Classic approach to building a symbol table uses hashing

- Some concern about worst-case behavior
  - Collisions in the hash function can lead to linear search
  - Some authors advocate "perfect" hash for keyword lookup
- Automata theory lets us avoid worst-case behavior



Hash-less Symbol Tables

One alternative is Paige & Cai's *multiset discrimination*

- Order the name space offline
- Assign indices to each name
- Replace the names in the input with their encoded indices

Digression on page 241 of EaC

Using DFA techniques, we can build a guaranteed linear-time replacement for the hash function *h*

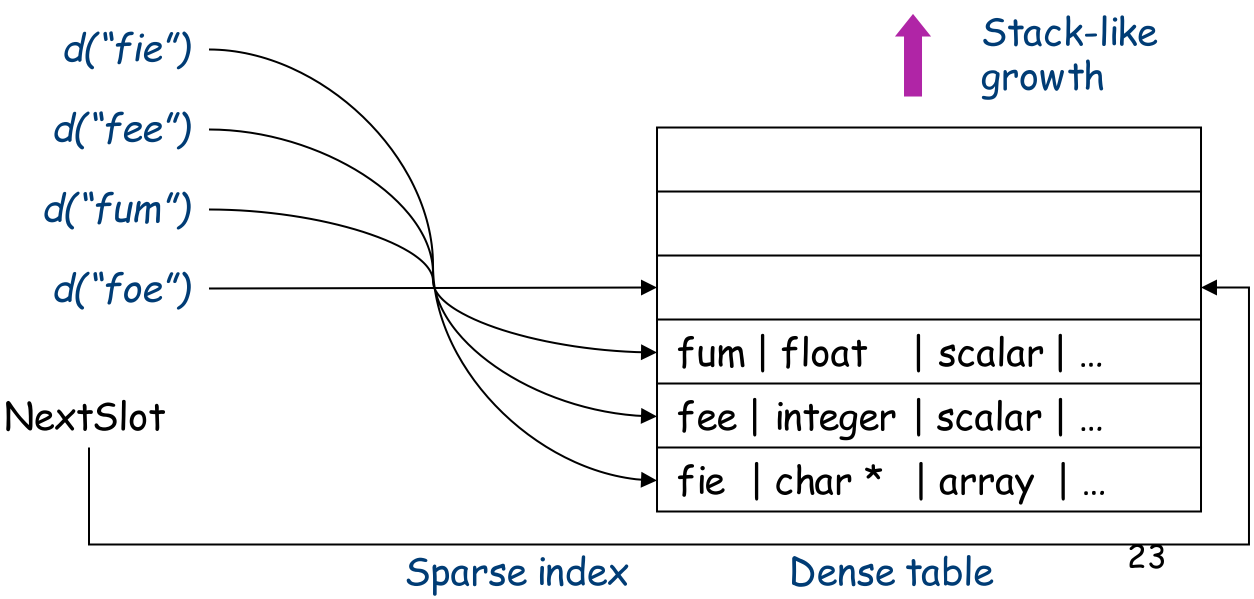
- DFA that results from a list of words is acyclic
  - RE looks like $r_1 \mid r_2 \mid r_3 \mid \ldots \mid r_k$
  - Could process input twice, once to build DFA, once to use it
- We can do even better

Hash-less Symbol Tables

Classic approach to building a symbol table uses hashing

- Some concern about worst-case behavior
  - Collisions in the hash function can lead to linear search
  - Some authors advocate "perfect" hash for keyword lookup
- Automata theory lets us avoid worst-case behavior

Replace the hash function, *h*, and the sparse index with an efficient direct map, *d*, …



Hash-less Symbol Tables

Incremental construction of an acyclic DFA

- To add a word, run it through the DFA
  - At some point, it will face a transition to the error state
  - At that point, start building states & transitions to recognize it
- Requires a memory access per character in the key
  - If DFA grows too large, memory access costs become excessive
  - For small key sets (e.g., names in a procedure), not a problem
- Optimizations
  - Last state on each path can be explicit
    - → Substantial reduction in memory costs
    - → Instantiate when path is lengthened
  - Trade off granularity against size of state representation
  - Encode capitalization separately
    - → Bit strings tied to final state?