Intermediate Code Generation

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The Phases of a Compiler

Phase	Output	Sample
Programmer	Source string	`A=B+C;`
Scanner (performs *lexical analysis*)	Token string	`'A', '=', 'B', '+', 'C', ';'` And *symbol table* for identifiers

Parser (performs *syntax analysis* based on the grammar of the programming language)	Parse tree or abstract syntax tree	`;`
		`|`
		`=`
		`/ \`
		`A   +`
		`/ \`
		`B   C`

Semantic analyzer (type checking, etc)	Parse tree or abstract syntax tree	

Intermediate code generator	Three-address code, quads, or RTL	`int2fp B      t1`
		`+      t1  C  t2`
		`:=     t2     A`

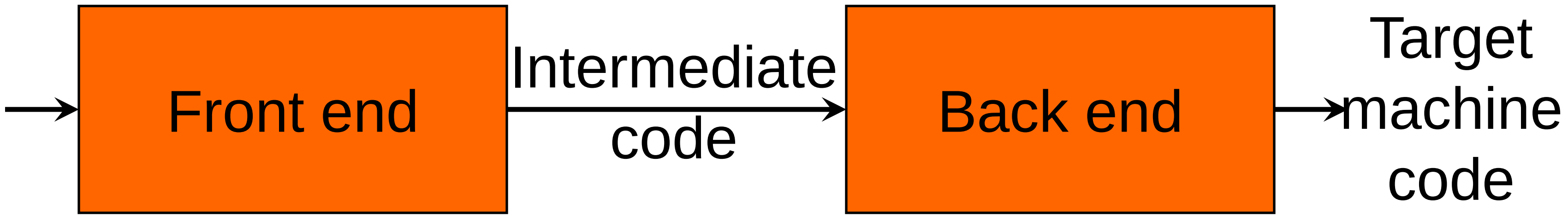
Optimizer	Three-address code, quads, or RTL	`int2fp B      t1` `+      t1 #2.3 A`

Code generator	Assembly code	`MOVF  #2.3,r1`
		`ADDF2 r1,r2`
		`MOVF  r2,A`

Peephole optimizer	Assembly code	`ADDF2 #2.3,r2` `MOVF  r2,A`

Intermediate Code Generation

- Facilitates *retargeting*: enables attaching a back end for the new machine to an existing front end



- Enables machine-independent code optimization

Intermediate Representations

- *Graphical representations* (e.g. AST)
- *Postfix notation*: operations on values stored on operand stack (similar to JVM bytecode)
- *Three-address code*: (e.g. *triples* and *quads*)

  $x := y \text{ op } z$
- *Two-address code*:

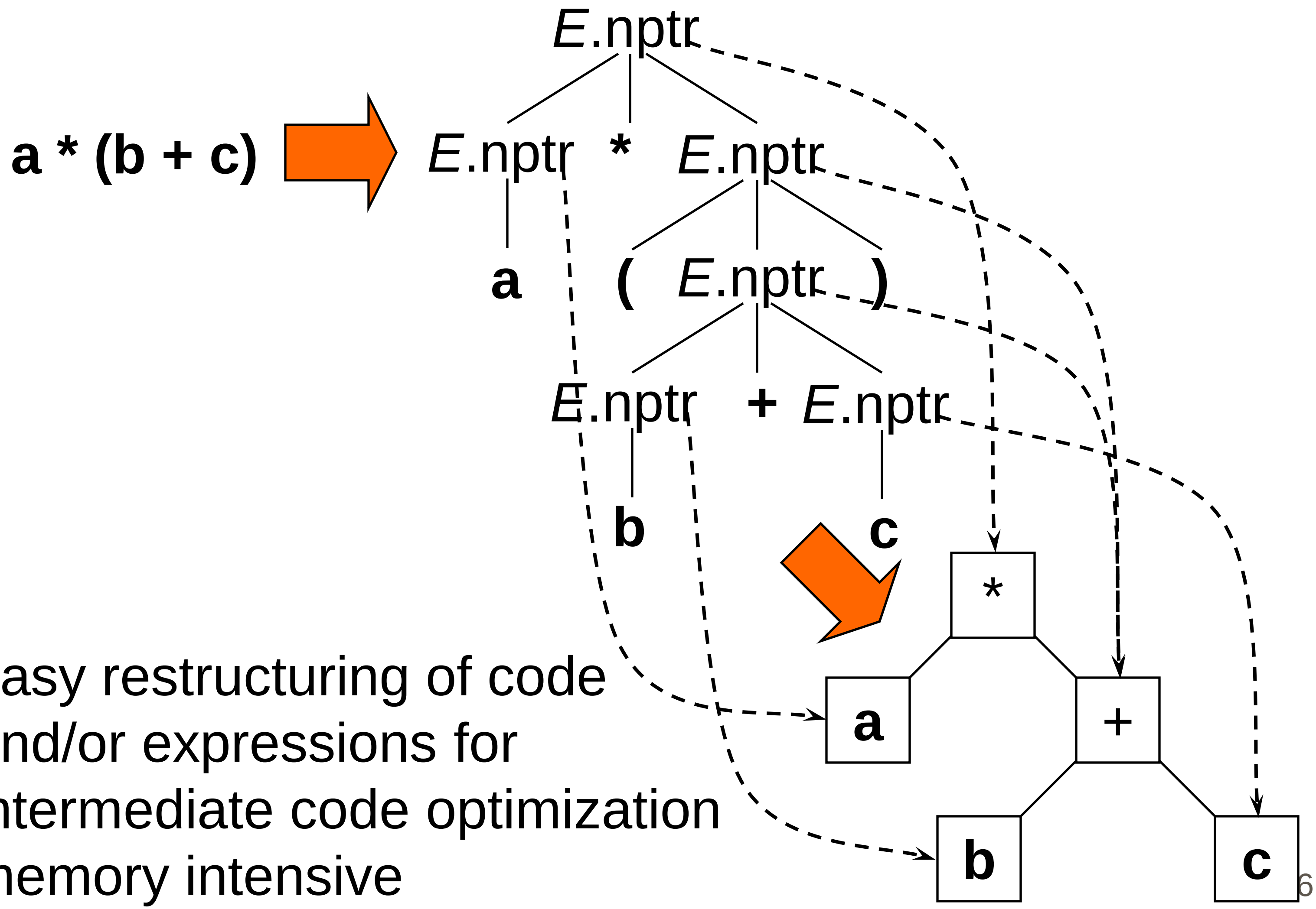
  $x := \text{op } y$

  which is the same as $x := x \text{ op } y$

Syntax-Directed Translation of Abstract Syntax Trees

Production	Semantic Rule
$S \rightarrow$ **id** **:=** E	S.nptr := *mknode*(':=', *mkleaf*(**id**, **id**.entry), E.nptr)
$E \rightarrow E_1$ **+** E_2	E.nptr := *mknode*('+', E_1.nptr, E_2.nptr)
$E \rightarrow E_1$ ***** E_2	E.nptr := *mknode*('*', E_1.nptr, E_2.nptr)
$E \rightarrow$ **-** E_1	E.nptr := *mknode*('uminus', E_1.nptr)
$E \rightarrow$ **(** E_1 **)**	E.nptr := E_1.nptr
$E \rightarrow$ **id**	E.nptr := *mkleaf*(**id**, **id**.entry)

Abstract Syntax Trees

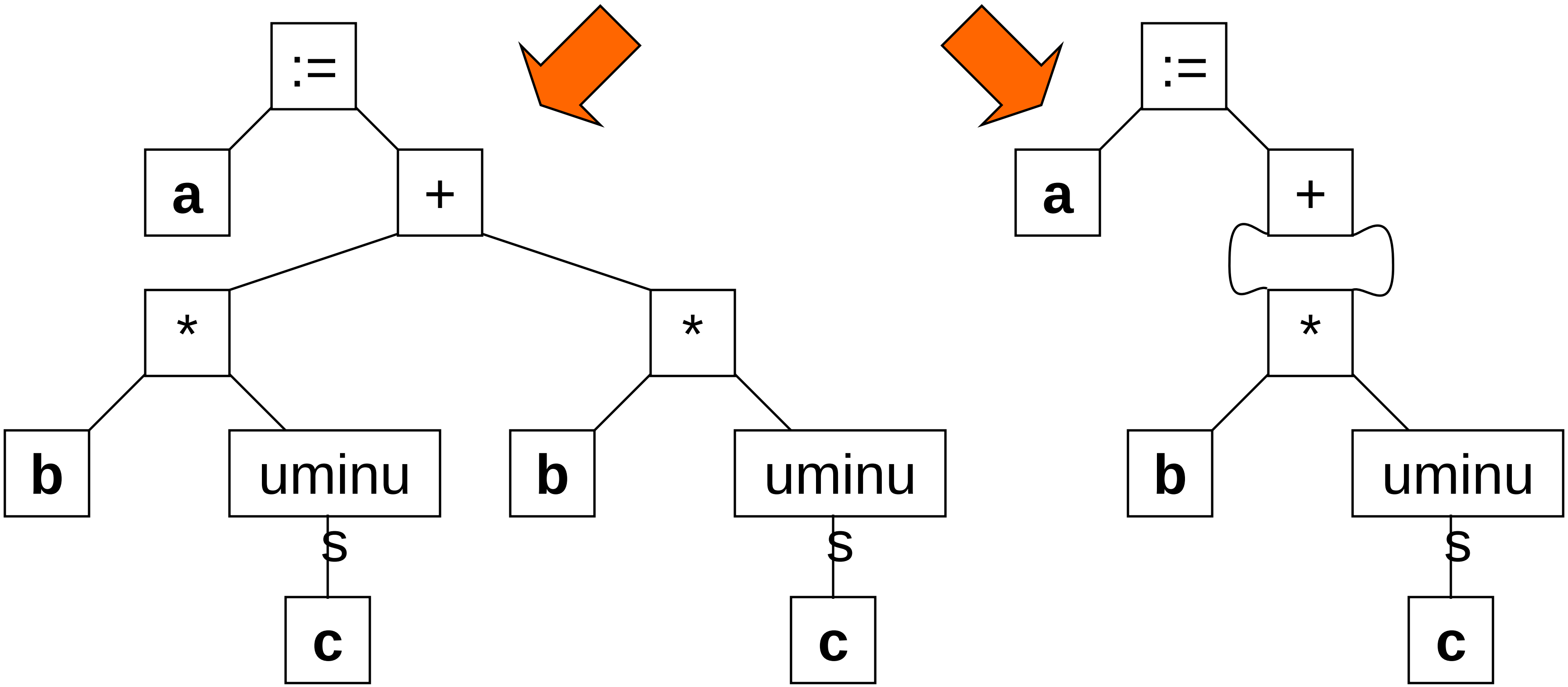


Pro: easy restructuring of code and/or expressions for intermediate code optimization

Cons: memory intensive

Abstract Syntax Trees versus DAGs

a := b * -c + b * -c



Tree DAG

Postfix Notation

a := b * -c + b * -c

a b c uminus * b c uminus * + assign

Postfix notation represents operations on a stack

Pro: easy to generate

Cons: stack operations are more difficult to optimize

Bytecode (for example)

```
iload 2        // push b
iload 3        // push c
ineg           // uminus
imul           // *
iload 2        // push b
iload 3        // push c
ineg           // uminus
imul           // *
iadd           // +
istore 1       // store a
```

Three-Address Code

a := b * -c + b * -c

```
t1  := - c
t2  := b * t1
t3  := - c
t4  := b * t3
t5  := t2 + t4
a   := t5
```

Linearized representation of a syntax tree

```
t1  := - c
t2  := b * t1
t5  := t2 + t2
a   := t5
```

Linearized representation of a syntax DAG

Three-Address Statements

- Assignment statements: x `:=` y *op* z, x `:=` *op* y
- Indexed assignments: x `:=` y[i], x[i] `:=` y
- Pointer assignments: x `:=` `&`y, x `:=` `*`y, `*`x `:=` y
- Copy statements: x `:=` y
- Unconditional jumps: **`goto`** *lab*
- Conditional jumps: **`if`** x *relop* y **`goto`** *lab*
- Function calls: **`param`** *x*… **`call`** *p*, *n*
  `return` y

Syntax-Directed Translation into Three-Address Code

Productions

$S \rightarrow$ **id :=** E
  | **while** E **do** S
$E \rightarrow E$ **+** E
  | E ***** E
  | **-** E
  | **(** E **)**
  | **id**
  | **num**

Synthesized attributes:

S.code three-address code for
S.begin label to start of *S* or nil
S.after label to end of *S* or nil
E.code three-address code for
E.place a name holding the val

gen(*E*.place ':=' E_1.place '+' E_2.place

Code generation

```
t3 := t1 + t2
```

Syntax-Directed Translation into Three-Address Code (cont'd)

Productions	Semantic rules
$S \rightarrow$ **id** **:=** E	S.code := E.code || *gen*(**id**.place ':=' E.place); S.begin := S.after :
$S \rightarrow$ **while** E **do** S_1	(*see next slide*)
$E \rightarrow E_1$ **+** E_2	E.place := *newtemp*(); E.code := E_1.code || E_2.code || *gen*(E.place ':=' E_1.place '+' E_2.pla
$E \rightarrow E_1$ ***** E_2	E.place := *newtemp*(); E.code := E_1.code || E_2.code || *gen*(E.place ':=' E_1.place '*' E_2.pla
$E \rightarrow$ **-** E_1	E.place := *newtemp*(); E.code := E_1.code || *gen*(E.place ':=' 'uminus' E_1.place)
$E \rightarrow$ **(** E_1 **)**	E.place := E_1.place E.code := E_1.code
$E \rightarrow$ **id**	E.place := **id**.name E.code := ''
$E \rightarrow$ **num**	E.place := *newtemp*(); E.code := *gen*(E.place ':=' **num**.value)

Syntax-Directed Translation into Three-Address Code (cont'd)

Production

$S \rightarrow$ **while** E **do** S_1

Semantic rule

S.begin := *newlabel*()
S.after := *newlabel*()
S.code := *gen*(*S*.begin ':') ||
E.code ||
gen('if' *E*.place '=' '0' 'goto' *S*.after) ||
S_1.code ||
gen('goto' *S*.begin) ||
gen(*S*.after ':')

S.begin:	*E*.code
	if *E*.place = 0 **goto** *S*.after
	S.code
	goto *S*.begin
S.after:	…

Example

```
i := 2 * n + k
while i do
    i := i - k
```

```
     t1  := 2
     t2  := t1 * n
     t3  := t2 + k
     i   := t3
L1:  if i = 0 goto L2
     t4  := i - k
     i   := t4
     goto L1
L2:
```

Implementation of Three-Address Statements: Quads

#	*Op*	*Arg1*	*Arg2*	*Res*
(0)	uminus	c		t1
(1)	*	b	t1	t2
(2)	uminus	c		t3
(3)	*	b	t3	t4
(4)	+	t2	t4	t5
(5)	:=	t5		a

Quads (quadruples)

Pro: easy to rearrange code for global optimization

Cons: lots of temporaries

Implementation of Three-Address Statements: Triples

#	*Op*	*Arg1*	*Arg2*
(0)	uminus	c	
(1)	*	b	(0)
(2)	uminus	c	
(3)	*	b	(2)
(4)	+	(1)	(3)
(5)	:=	a	(4)

Triples

Pro: temporaries are implicit

Cons: difficult to rearrange code

Implementation of Three-Address Stmts: Indirect Triples

#	*Stmt*
(0)	(14)
(1)	(15)
(2)	(16)
(3)	(17)
(4)	(18)
(5)	(19)

Program

#	*Op*	*Arg1*	*Arg2*
(14)	uminus	c	
(15)	*	b	(14)
(16)	uminus	c	
(17)	*	b	(16)
(18)	+	(15)	(17)
(19)	:=	a	(18)

Triple container

Pro: temporaries are implicit & easier to rearrange code

Names and Scopes

- The three-address code generated by the syntax-directed definitions shown on the previous slides is somewhat simplistic, because it assumes that the names of variables can be easily resolved by the back end in global or local variables
- We need local symbol tables to record global declarations as well as local declarations in procedures, blocks, and structs to resolve names

Symbol Tables for Scoping

```
struct S
{ int a;
  int b;
} s;

void swap(int& a, int& b)
{ int t;
  t = a;
  a = b;
  b = t;
}

void somefunc()
{ …
  swap(s.a, s.b);
  …
}
```

We need a symbol table for the *fields* of struct S

Need symbol table for *global* variables and functions

Need symbol table for *arguments* and *locals* for each function

Check: **s** is global and has fields **a** and **b**

Using symbol tables we can generate code to access **s** and its fields

Offset and Width for Runtime Allocation

```
struct S
{ int a;
  int b;
} s;

void swap(int& a, int& b)
{ int t;
  t = a;
  a = b;
  b = t;
}

void somefunc()
{ …
  swap(s.a, s.b);
  …
}
```

The fields **a** and **b** of struct S are located at *offsets* 0 and 4 from the start of S

The *width* of S is 8

a	(0)
b	(4)

Subroutine frame holds arguments **a** and **b** and local **t** at *offsets* 0, 4, and 8

Subroutine frame

fp[0]=	a	(0)
fp[4]=	b	(4)
fp[8]=	t	(8)

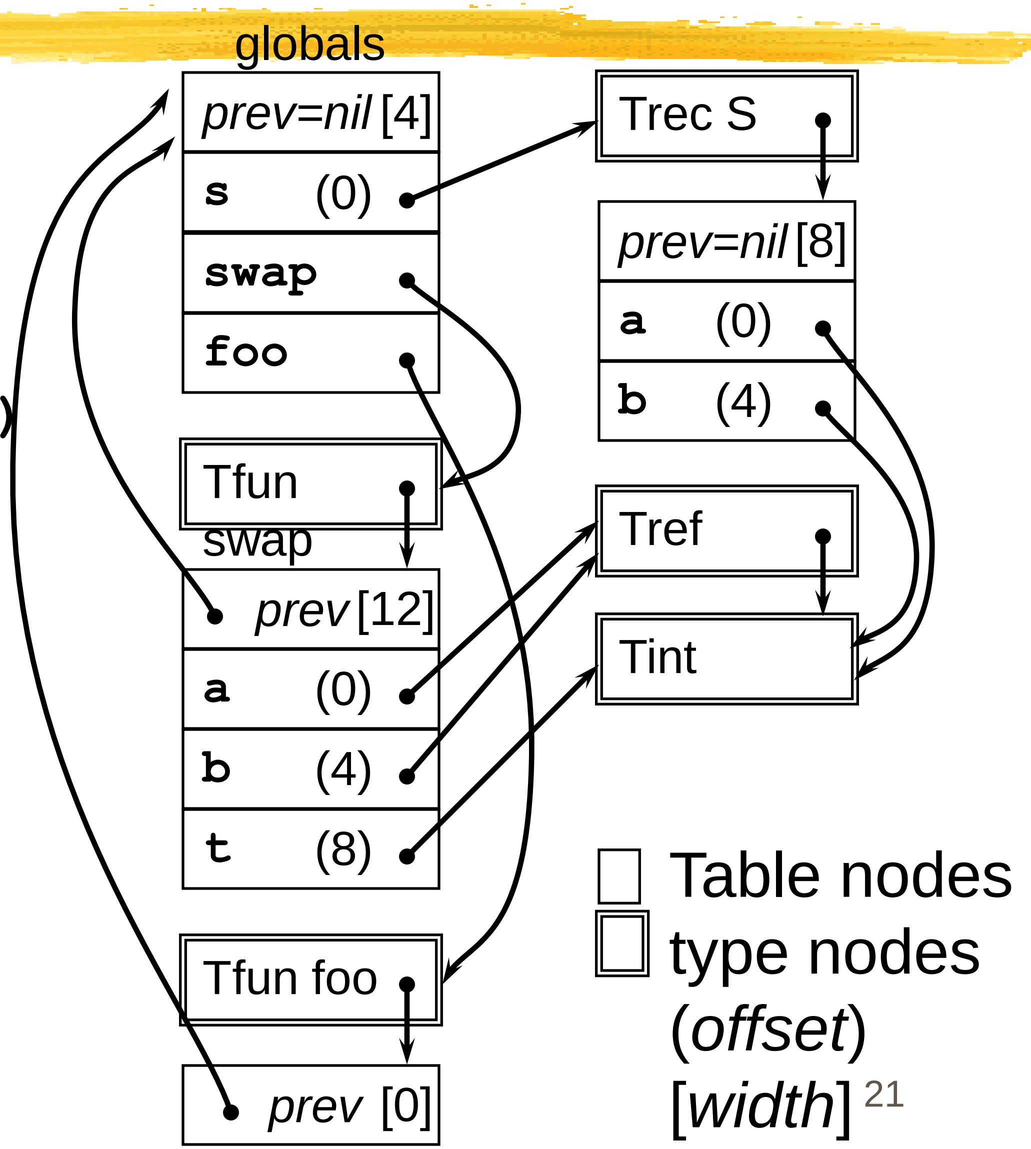
The *width* of the frame is 12

Example

```
struct S
{ int a;
  int b;
} s;

void swap(int& a, int& b)
{ int t;
  t = a;
  a = b;
  b = t;
}

void foo()
{ …
  swap(s.a, s.b);
  …
}
```



Hierarchical Symbol Table Operations

- *mktable*(*previous*) returns a pointer to a new table that is linked to a previous table in the outer scope
- *enter*(*table*, *name*, *type*, *offset*) creates a new entry in *table*
- *addwidth*(*table*, *width*) accumulates the total width of all entries in *table*
- *enterproc*(*table*, *name*, *newtable*) creates a new entry in *table* for procedure with local scope *newtable*
- *lookup*(*table*, *name*) returns a pointer to the entry in the table for *name* by following linked tables

Syntax-Directed Translation of Declarations in Scope

Productions

$P \rightarrow D$ **;** S

$D \rightarrow D$ **;** D

| **id :** T

| **proc id ;** D **;** S

$T \rightarrow$ **integer**

| **real**

| **array [num] of** T

| **^** T

| **record** D **end**

$S \rightarrow S$ **;** S

| **id :=** E

| **call id (** A **)**

Productions *(cont'd)*

$E \rightarrow E$ **+** E

| E ***** E

| **-** E

| **(** E **)**

| **id**

| E **^**

| **&** E

| E **. id**

$A \rightarrow A$ **,** E

| E

Synthesized attributes:

T.type pointer to type

T.width storage width of type (bytes)

E.place name of temp holding value of *E*

Global data to implement scoping:

tblptr stack of pointers to tables

offset stack of offset values

Syntax-Directed Translation of Declarations in Scope (cont'd)

$P \rightarrow$ { *t* := *mktable*(nil); *push*(*t*, *tblptr*); *push*(0, *offset*) }
D **;** *S*

$D \rightarrow$ **id :** *T*
{ *enter*(*top*(*tblptr*), **id**.name, *T*.type, *top*(*offset*));
top(*offset*) := *top*(*offset*) + *T*.width }

$D \rightarrow$ **proc id ;**
{ *t* := *mktable*(*top*(*tblptr*)); *push*(*t*, *tblptr*); *push*(0, *offset*)
D_1 **;** *S*
{ *t* := *top*(*tblptr*); *addwidth*(*t*, *top*(*offset*));
pop(*tblptr*); *pop*(*offset*);
enterproc(*top*(*tblptr*), **id**.name, *t*) }

$D \rightarrow D_1$ **;** D_2

Syntax-Directed Translation of Declarations in Scope (cont'd)

$T \rightarrow$ **integer** { T.type := '*integer*'; T.width := 4 }

$T \rightarrow$ **real** { T.type := '*real*'; T.width := 8 }

$T \rightarrow$ **array [num] of** T_1

{ T.type := *array*(**num**.val, T_1.type);
T.width := **num**.val * T_1.width }

$T \rightarrow$ **^** T_1

{ T.type := *pointer*(T_1.type); T.width := 4 }

$T \rightarrow$ **record**

{ *t* := *mktable*(nil); *push*(*t*, *tblptr*); *push*(0, *offset*) }

D **end**

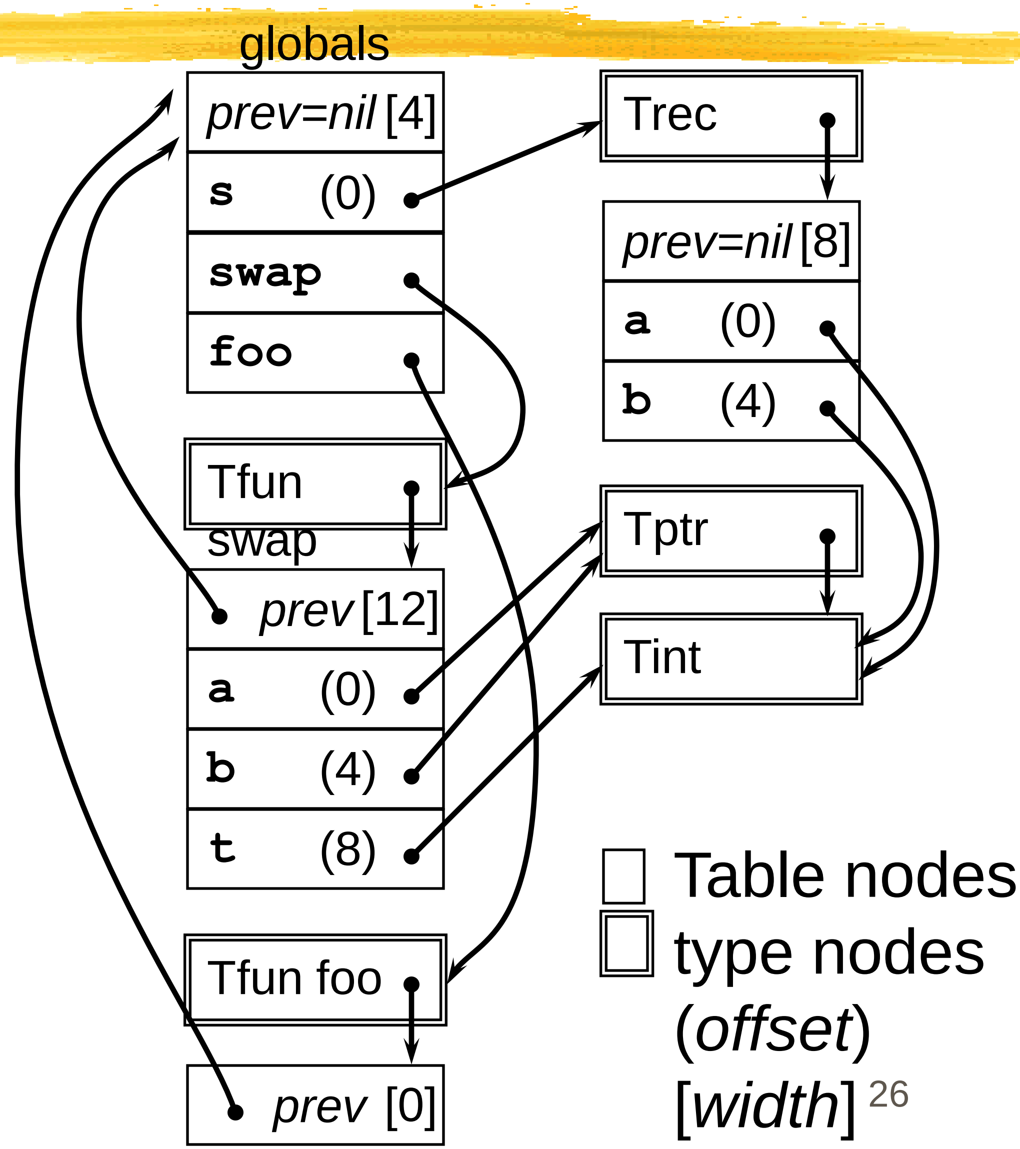
{ T.type := *record*(*top*(*tblptr*)); T.width := *top*(*offset*);
addwidth(*top*(*tblptr*), *top*(*offset*)); *pop*(*tblptr*); *pop*(*offset*

Example

```
s: record
      a: integer;
      b: integer;
   end;

proc swap;
   a: ^integer;
   b: ^integer;
   t: integer;
   t := a^;
   a^ := b^;
   b^ := t;

proc foo;
   call swap(&s.a, &s.b);
```



Syntax-Directed Translation of Statements in Scope

S → *S* **;** *S*
S → **id :=** *E*
{ *p* := *lookup*(*top*(*tblptr*), **id**.name);
if *p* = nil **then**
error()
else if *p*.level = 0 **then** *// global variable*
emit(**id**.place ':=' *E*.place)
else *// local variable in subroutine frame*
emit(fp[*p*.offset] ':=' *E*.place) }

Globals

s	(0)
x	(8)
y	(12)

Subroutine frame

fp[0]=	**a**	(0)
fp[4]=	**b**	(4)
fp[8]=	**t**	(8)
…		

Syntax-Directed Translation of Expressions in Scope

$E \rightarrow E_1$ **+** E_2 { E.place := *newtemp*();
emit(E.place ':=' E_1.place '+' E_2.place) }

$E \rightarrow E_1$ ***** E_2 { E.place := *newtemp*();
emit(E.place ':=' E_1.place '*' E_2.place) }

$E \rightarrow$ **-** E_1 { E.place := *newtemp*();
emit(E.place ':=' 'uminus' E_1.place) }

$E \rightarrow$ **(** E_1 **)** { E.place := E_1.place }

$E \rightarrow$ **id** { *p* := *lookup*(*top*(*tblptr*), **id**.name);
if *p* = nil **then** *error*()
else if *p*.level = 0 **then** *// global variable*
E.place := **id**.place
else *// local variable in frame*
E.place := fp[*p*.offset] }