5. Semantic Analysis

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Thanks to Jens Palsberg and Tony Hosking for their kind permission to reuse and adapt the CS132 and CS502 lecture notes.
http://www.cs.ucla.edu/~palsberg/
http://www.cs.purdue.edu/homes/hosking/

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William Tell is a folk hero of Switzerland; she was an exceptional marksman.

Conference in Vienna in 1964 best summarized by T. B. Steel:

“*I don’t fully know myself how to describe the semantics of a language. I daresay nobody does or we wouldn’t be here*”

<u>*The Genesis of Atribute Grammars*</u>
Donald E. Knuth

Roadmap

> Context-sensitive analysis
> Strategies for semantic analysis
> Attribute grammars
> Symbol tables and type-checking

See, *Modern compiler implementation in Java* (Second edition), Chapter 5.

Roadmap

- **Context-sensitive analysis**
- Strategies for semantic analysis
- Attribute grammars
- Symbol tables and type-checking

```
{
...
  x := y [1];
  z := x + y;
...
}
```

Semantic Analysis

*Compilation is **driven by the syntactic structure** of the program as discovered by the parser*

Semantic routines:

- interpret meaning of the program based on its syntactic structure
- two purposes:
  - *finish **analysis** by deriving context-sensitive information*
  - *begin **synthesis** by generating the IR or target code*
- associated with individual productions of a context free grammar or sub-trees of a syntax tree

Context-sensitive analysis

What context-sensitive questions might the compiler ask?

1. Is `x` scalar, an array, or a function?
2. Is `x` declared before it is used?
3. Are any names declared but not used?
4. Which declaration of `x` is being referenced?
5. Is an expression type-consistent?
6. Does the dimension of a reference match the declaration?
7. Where can `x` be stored? (heap, stack, ...)
8. Does `*p` reference the result of a `malloc()`?
9. Is `x` defined before it is used?
10. Is an array reference in bounds?
11. Does function `foo` produce a constant value?
12. Can `p` be implemented as a memo-function?

These questions cannot be answered with a context-free grammar

Context-sensitive analysis

> What are the challenges?
  - questions and answers involve non-local information
  - answers depend on values, not syntax
  - answers may involve computation

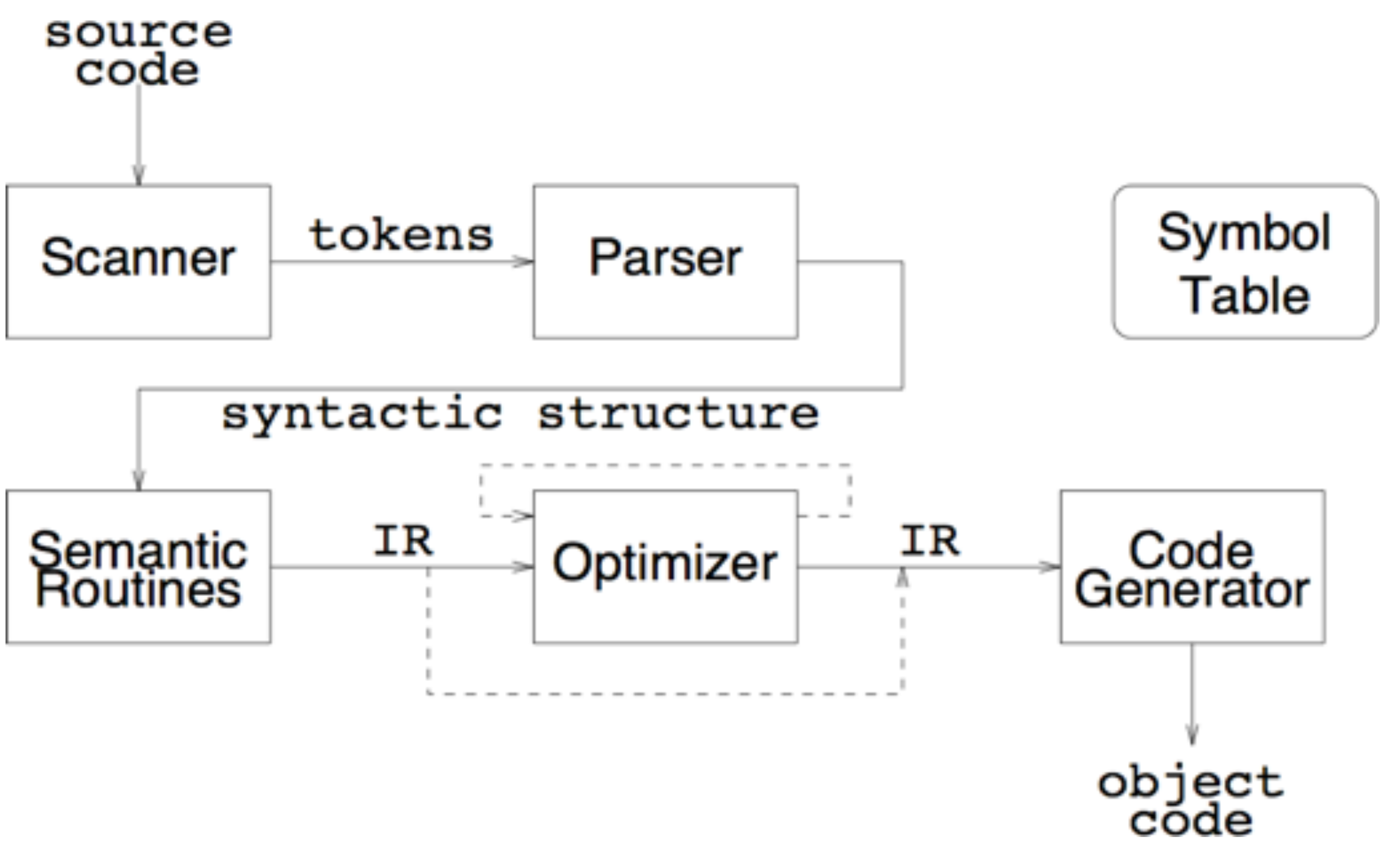
> Several approaches:
  - *symbol tables:* central store for facts; express checking code
  - *attribute grammars:* specify non-local computations; automatic evaluators
  - *language design:* simplify language; avoid problems

Roadmap

> Context-sensitive analysis
> **Strategies for semantic analysis**
> Attribute grammars
> Symbol tables and type-checking

Alternatives for semantic processing

- One-pass compiler and synthesis
- Two-pass
  - compiler + peephole
  - compiler & IR synthesis + code generation pass
- Multi-pass
  - analysis
  - synthesis



One-pass compilers

- Interleave scanning, parsing and translation
  - no explicit IR
  - generate target code directly
    - *emit short sequences of instructions on each parser action*
    - *little or no optimization possible (minimal context)*

- Can add *peephole optimization pass*
  - extra pass over generated code through small window (“peephole”) of instructions
  - smooths out “rough edges” between code emitted by subsequent calls to code generator

Two-pass: analysis & IR synthesis + code generation

> Generate explicit IR as interface to code generator
  - linear (e.g., tuples)
  - can emit multiple tuples at a time for better code context
> Advantages
  - easier retargeting (IR must be expressive enough for different machines!)
  - can add optimization pass later (multi-pass synthesis)

Multi-pass analysis

- Several passes, read/write intermediate files
  1. scan source file, generate tokens
     - *place identifiers and constants in symbol table*
  2. parse token file
     - *generate semantic actions or linearized parse tree*
  3. process declarations to symbol table
  4. semantic checking with IR synthesis

- Motivations:
  - Historical: constrained address spaces
  - Language: *e.g.*, declaration after use
  - Multiple analyses over IR tree

Multi-pass synthesis

> Passes operate on linear or tree-structured IR
> Options:
  - code generation and peephole optimization
  - multi-pass IR transformation
    - *machine-independent then dependent optimizations*
  - high-level to low-level IR transformation before code generation
    - *e.g., in **gcc** high-level trees drive generation of low-level Register Transfer Language for machine-independent optimization*
  - language-independent front ends
  - retargetable back ends

Roadmap

> Context-sensitive analysis
> Strategies for semantic analysis
> **Attribute grammars**
> Symbol tables and type-checking

Attribute grammars

> Add attributes to the syntax tree or PEG:
  - —can add attributes (fields) to each node
  - —specify equations to define values
  - —propagate values up (synthesis) or down (inheritance)

> **Example:** ensuring that constants are immutable
  - —add *type* and *class* attributes to expression nodes
  - —add rules to production for `:=`
    1. *check that LHS.class is variable (not constant)*
    2. *check that LHS.type and RHS.type are compatible*

Attribute grammar actions

PRODUCTION	SEMANTIC RULES
$D \rightarrow T\ L$	$L.\mathrm{in} := T.\mathrm{type}$
$T \rightarrow \textbf{int}$	$T.\mathrm{type} := \mathrm{integer}$
$T \rightarrow \textbf{real}$	$T.\mathrm{type} := \mathrm{real}$
$L \rightarrow L_1\ ,\ \textbf{id}$	$L_1.\mathrm{in} := L.\mathrm{in}$
	$\mathrm{addtype}(\textbf{id}.\mathrm{entry}, L.\mathrm{in})$
$L \rightarrow \textbf{id}$	$\mathrm{addtype}(\textbf{id}.\mathrm{entry}, L.\mathrm{in})$

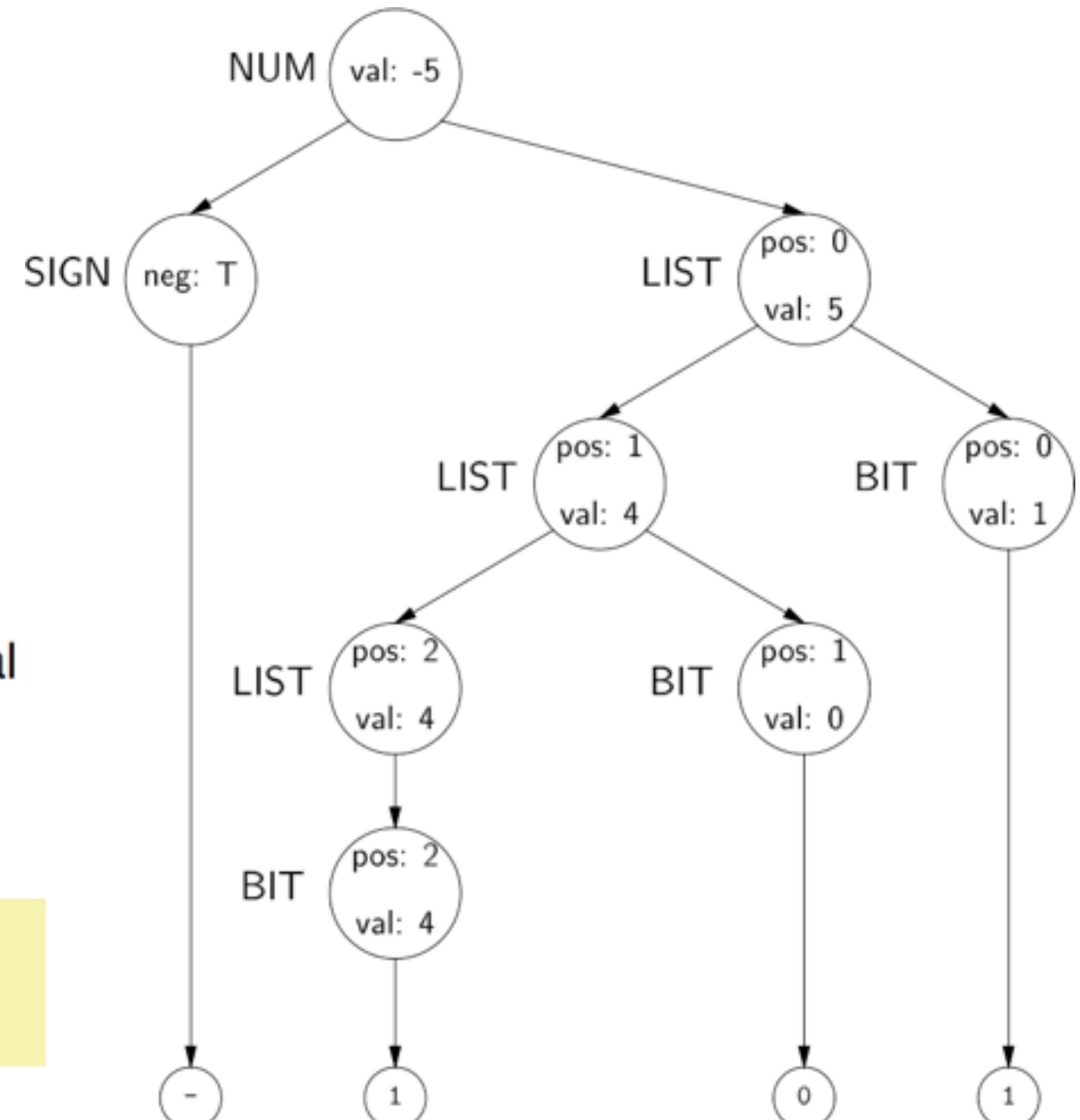
- tree attributes specified by grammar
- productions associated with attribute assignments
- each attribute defined uniquely and locally
- identical terms are labeled uniquely

Example: evaluating signed binary numbers

PRODUCTION	SEMANTIC RULES
NUM $\to$ SIGN LIST	LIST.pos := 0
	if SIGN.neg
	NUM.val := -LIST.val
	else
	NUM.val := LIST.val
SIGN $\to$ +	SIGN.neg := false
SIGN $\to$ -	SIGN.neg := true
LIST $\to$ BIT	BIT.pos := LIST.pos
	LIST.val := BIT.val
LIST $\to$ LIST$_1$ BIT	LIST$_1$.pos := LIST.pos + 1
	BIT.pos := LIST.pos
	LIST.val := LIST$_1$.val + BIT.val
BIT $\to$ 0	BIT.val := 0
BIT $\to$ 1	BIT.val := $2^{\mathrm{BIT}.pos}$

- *val* and *neg* are *synthetic* attributes
- *pos* is an *inherited* attribute

Attributed parse tree for -101

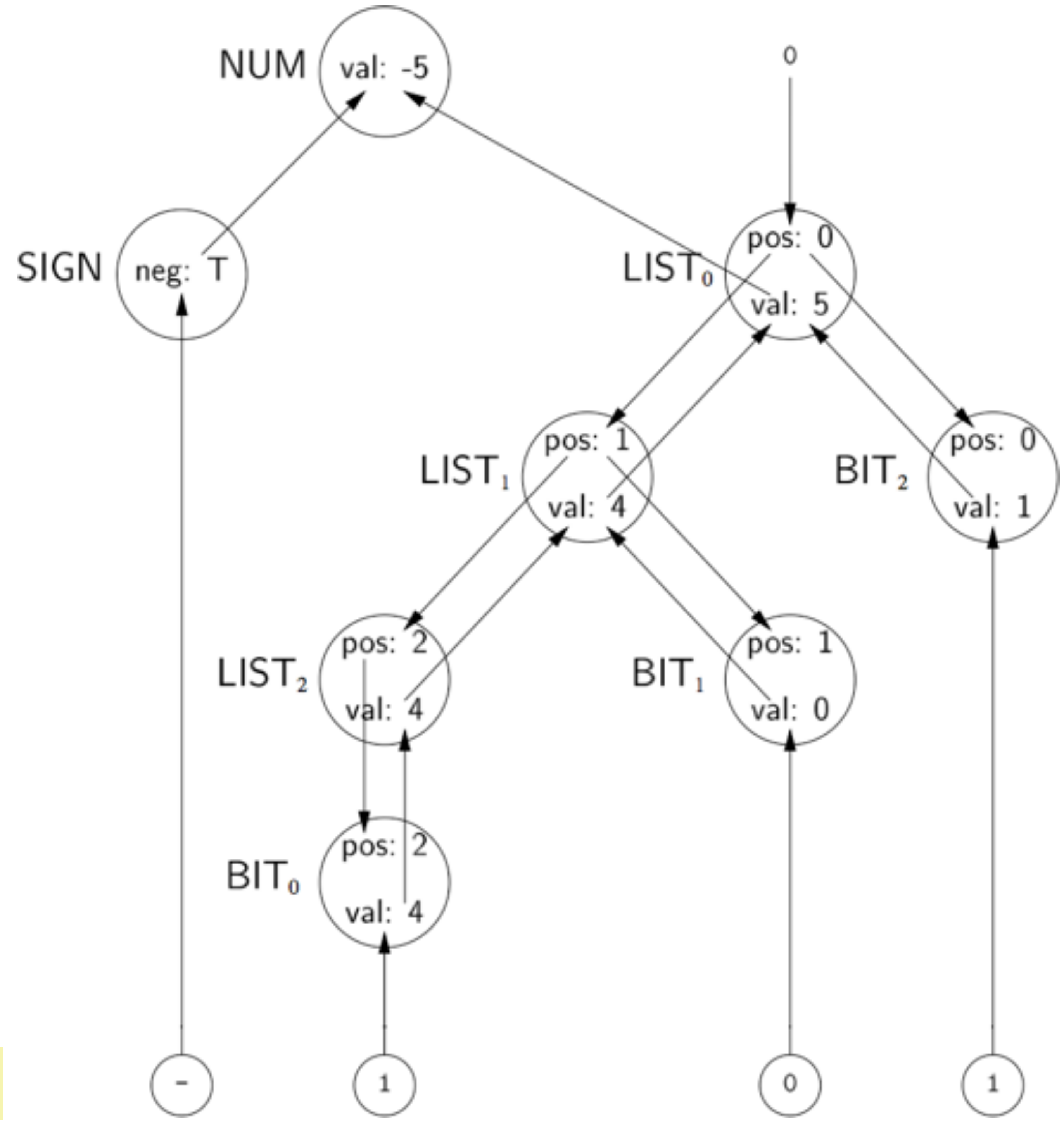


Attribute dependency graph

- *nodes* represent *attributes*
- *edges* represent *flow of values*
- graph must be *acyclic*
- *topologically sort* to order attributes
  - use this order to evaluate rules
  - order depends on both grammar and input string!

1. SIGN.neg	8. BIT_0.val
2. $LIST_0$.pos	9. $LIST_2$.val
3. $LIST_1$.pos	10. BIT_1.val
4. $LIST_2$.pos	11. $LIST_1$.val
5. BIT_0.pos	12. BIT_2.val
6. BIT_1.pos	13. $LIST_0$.val
7. BIT_2.pos	14. NUM.val

Evaluating in this order yields NUM.val = -5



Evaluation strategies

> ***Parse-tree methods***

1. build the parse tree
2. build the dependency graph
3. topologically sort the graph
4. evaluate it

> ***Rule-based methods***

1. analyse semantic rules at compiler-construction time
2. determine static ordering for each production's attributes
3. evaluate its attributes in that order at compile time

> ***Oblivious methods***

1. ignore the parse tree and the grammar
2. choose a convenient order (e.g., left-to-right traversal) and use it
3. repeat traversal until no more attribute values can be generated

Attribute grammars in practice

- *Advantages*
  - —clean formalism
  - —automatic generation of evaluator
  - —high-level specification
- *Disadvantages*
  - —evaluation strategy determines efficiency
  - —increase space requirements
  - —parse tree evaluators need dependency graph
  - —results distributed over tree
  - —circularity testing

Historically, attribute grammars have been judged too large and expensive for industrial-strength compilers.

Roadmap

- > Context-sensitive analysis
- > Strategies for semantic analysis
- > Attribute grammars
- > **Symbol tables and type-checking**

Symbol tables

> For compile-time efficiency, compilers often use a *symbol table*:
  — associates lexical *names* (symbols) with their *attributes*

> What items should be entered?
  — variable names
  — constants
  — procedure and function names
  — literal constants and strings
  — compiler-generated temporaries (we'll get there)

> Separate table of structure layouts for types (field offsets and lengths)

A symbol table is a compile-time structure

Symbol table information

> What kind of information might the compiler need?

—textual name

—data type

—dimension information *(for aggregates)*

—declaring procedure

—**lexical level** of declaration

—storage class *(heap, stack, text …)*

—offset in storage

—if record, pointer to structure table

—if parameter, by-reference or by-value?

—can it be aliased? to what other names?

—number and type of arguments to functions

Lexical Scoping

```
class C {
  int x;
  void m(int y) {
    int z;
    if (y>x) {
      int w=z+y;
      return w;
    }
    return y;
  }
}
```

With <u>*lexical scoping*</u> the definition of a name is determined by its *static scope.* A stack suffices to track the current definitions.

scope of y and z

scope of w

scope of x

Nested scopes: block-structured symbol tables

> What information is needed?
  - when we ask about a name, we want the *most recent declaration*
  - the declaration may be from the current scope or some enclosing scope
  - innermost scope overrides declarations from outer scopes

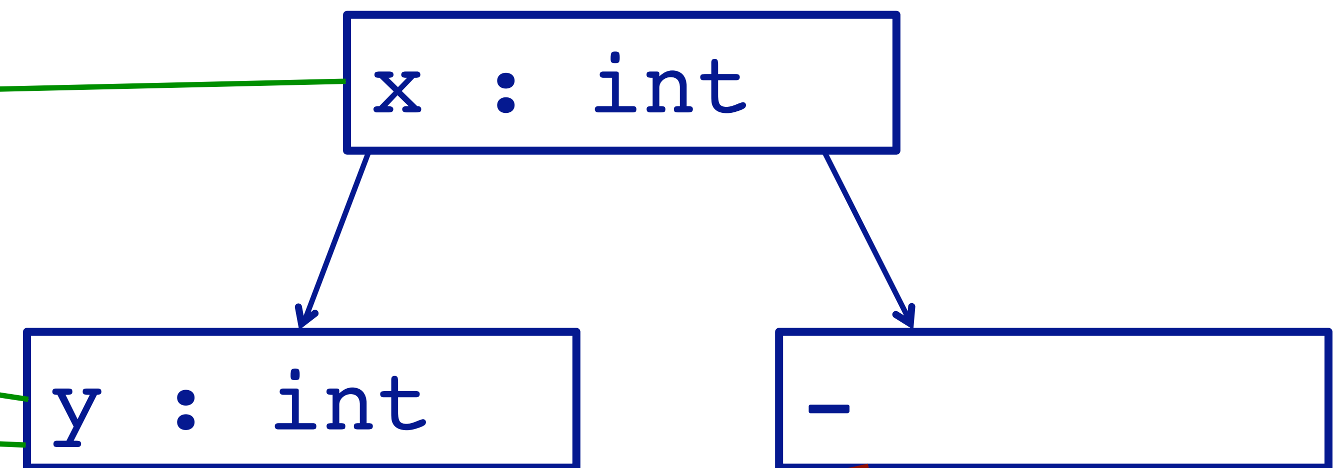
> Key point: *new declarations (usually) occur only in current scope*

> What operations do we need?
  - `void put(Symbol key, Object value)` — bind key to value
  - `Object get(Symbol key)` — return value bound to key
  - `void` **`beginScope()`** — remember current state of table
  - `void` **`endScope()`** — restore table to state at most recent scope that has not been ended

May need to preserve list of locals for the debugger

Checking variable declarations in a hierarchical symbol table

```
int x=1;
{
  int y = x;
  x = x+y;
}
{
  y = x – y;
}
```



Efficient Implementation of Symbol Tables

Implementation options

1. functional
2. imperative

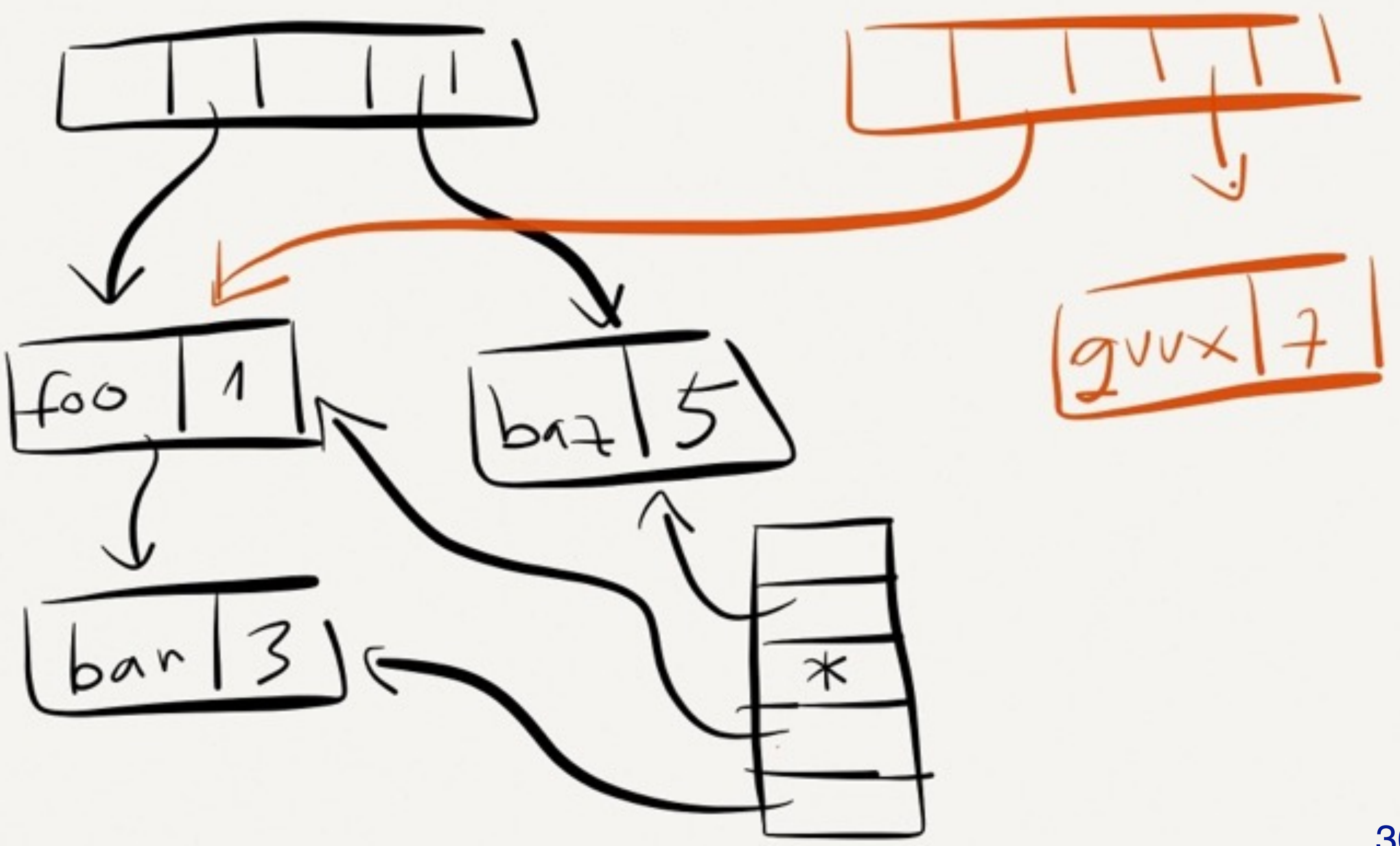
How to ensure efficiency, with thousands of distinct identifiers in a large program?

Efficient Implementation of Symbol Tables

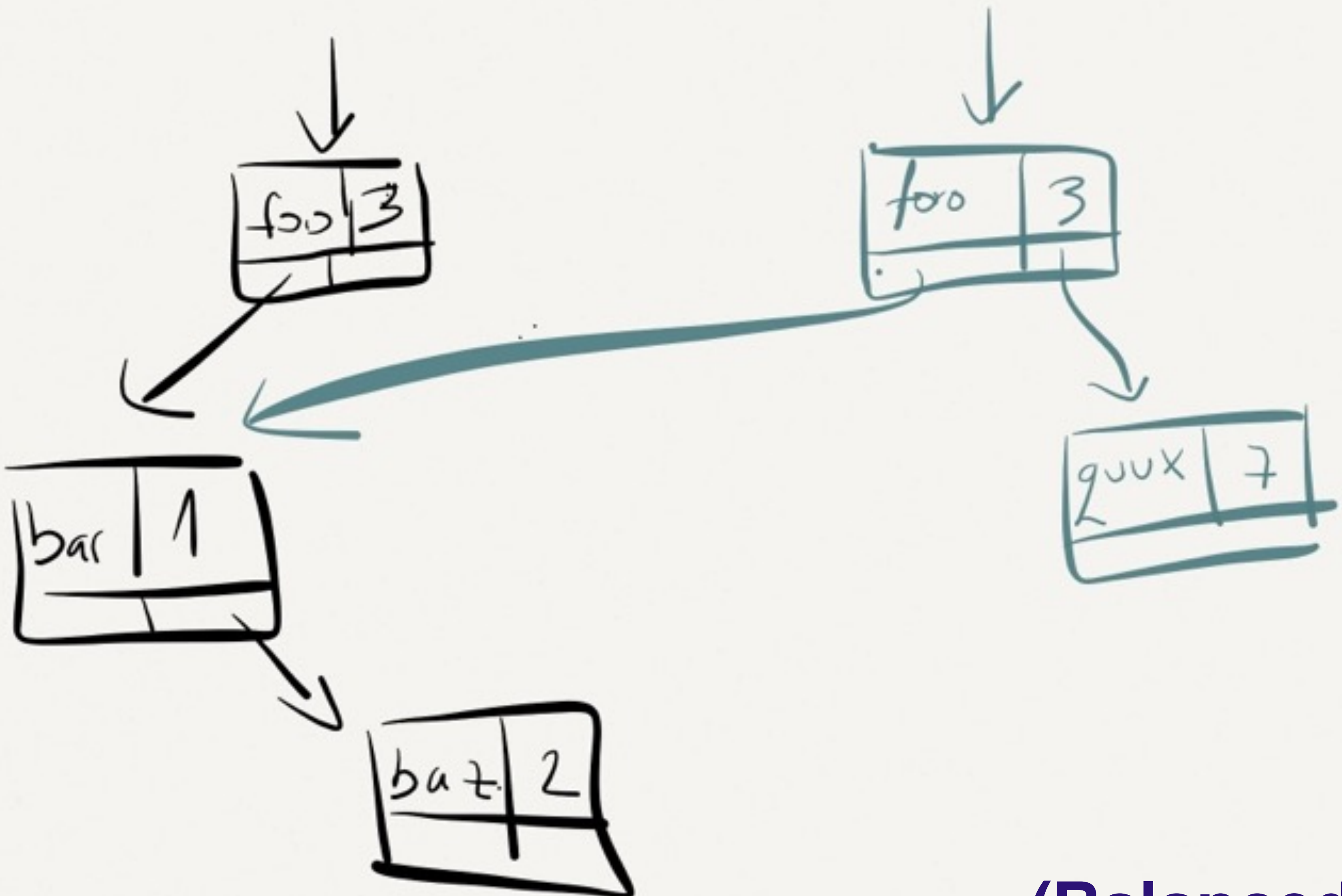
```
int foo, bar;
foo = ++bar;
if (bar>10) then
{
   boolean baz;
   baz = true;
}

// and assume
hash(foo)=hash(bar)
hash(baz)=hash(quux)
```

Hash tables support an **imperative** (destructive) implementation



Efficient Implementation of Symbol Tables (2)



(Balanced) binary trees support a functional (non-destructive) implementation. A persistence data structure.

Attribute information

> Attributes are internal representations of declarations
> Symbol table associates names with attributes

> Names may have different attributes depending on their meaning:
  — *variables:* type, procedure level, frame offset
  — *types:* type descriptor, data size/alignment
  — *constants:* type, value
  — *procedures:* formals (names/types), result type, block information (local decls.), frame size

Static and Dynamic Typing

A language is statically typed if it is always possible to *determine the (static) type* of an expression *based on the program text alone.*

A language is dynamically typed if *only values have fixed type*. Variables and parameters may take on different types at run-time, and must be checked immediately before they are used.

A language is "strongly typed" if it is impossible to perform an operation on the wrong kind of object.

Type consistency may be assured by

I. compile-time type-checking,
II. type inference, or
III. dynamic type-checking.

See: Programming Languages course

Type expressions

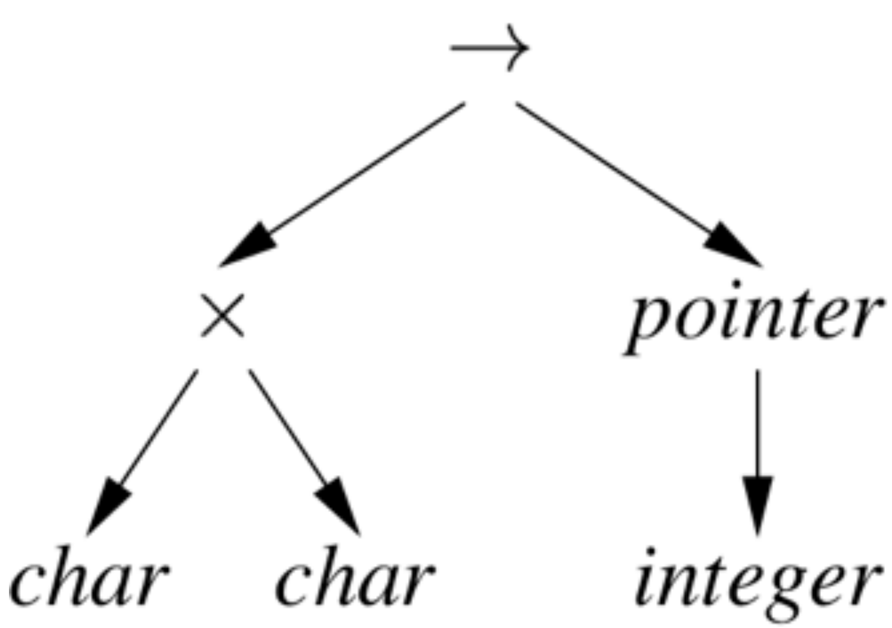
Type expressions are a textual representation for types:

1. basic types: *boolean*, *char*, *integer*, *real*, etc.
2. type names
3. constructed types (constructors applied to type expressions):
   a) array(I,T) denotes *array* of elements type T, index type I
      e.g., array (1...10,integer)
   b) $T_1 \times T_2$ denotes *Cartesian product* of type expressions T_1 and T_2
   c) record(…) denotes *record* with named fields
      e.g., record((a × integer), (b × real))
   d) pointer(T) denotes the type "*pointer* to object of type T"
   e) $D \rightarrow R$ denotes type of *function* mapping domain D to range R
      e.g., integer × integer → integer

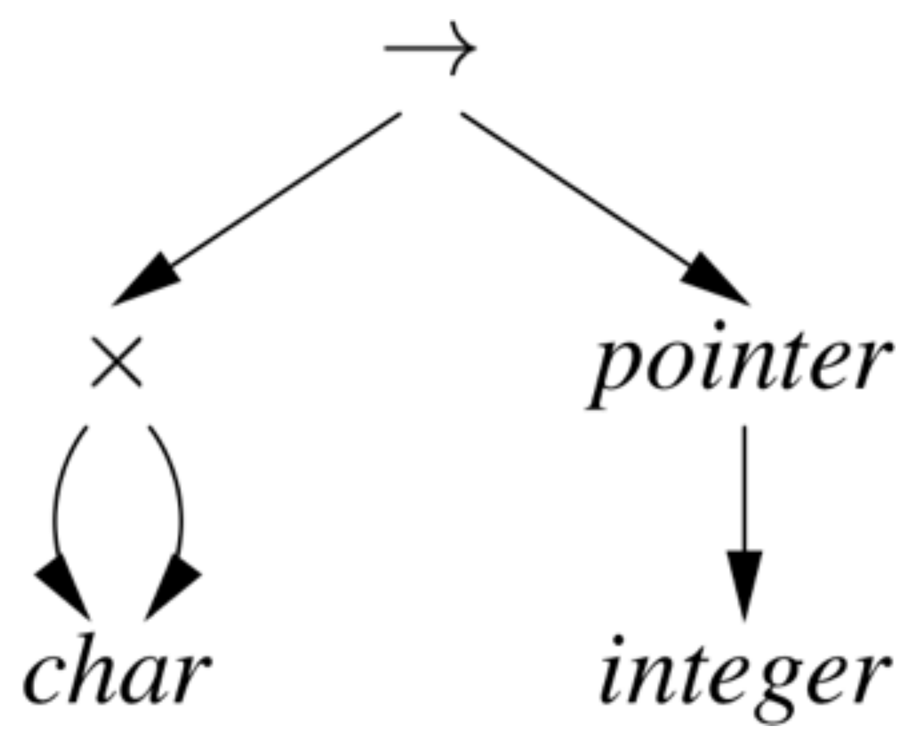
Type descriptors

Type descriptors are **compile-time structures** representing type expressions

e.g., *char × char → pointer(integer)*



or



Type compatibility

Type checking needs to determine *type equivalence*

Two approaches:

> *Name equivalence:* each type name is a distinct type

> *Structural equivalence:* two types are equivalent iff they have **the same structure** (after substituting type expressions for type names)

—$s \equiv t$ iff s and t are the same basic types

—$array(s_1,s_2) \equiv array(t_1,t_2)$ iff $s_1 \equiv t_1$ and $s_2 \equiv t_2$

—$s_1 \times s_2 \equiv t_1 \times t_2$ iff $s_1 \equiv t_1$ and $s_2 \equiv t_2$

—$pointer(s) \equiv pointer(t)$ iff $s \equiv t$

—$s_1 \rightarrow s_2 \equiv t_1 \rightarrow t_2$ iff $s_1 \equiv t_1$ and $s_2 \equiv t_2$

Type compatibility: example

Consider:

```
type link = ^cell
var next : link;
var last : link;
var p : ^cell;
var q, r : ^cell;
```

Under name equivalence:

- `next` and `last` have the same type
- `p`, `q` and `r` have the same type
- `p` and `next` have different type

Under structural equivalence all variables have the same type

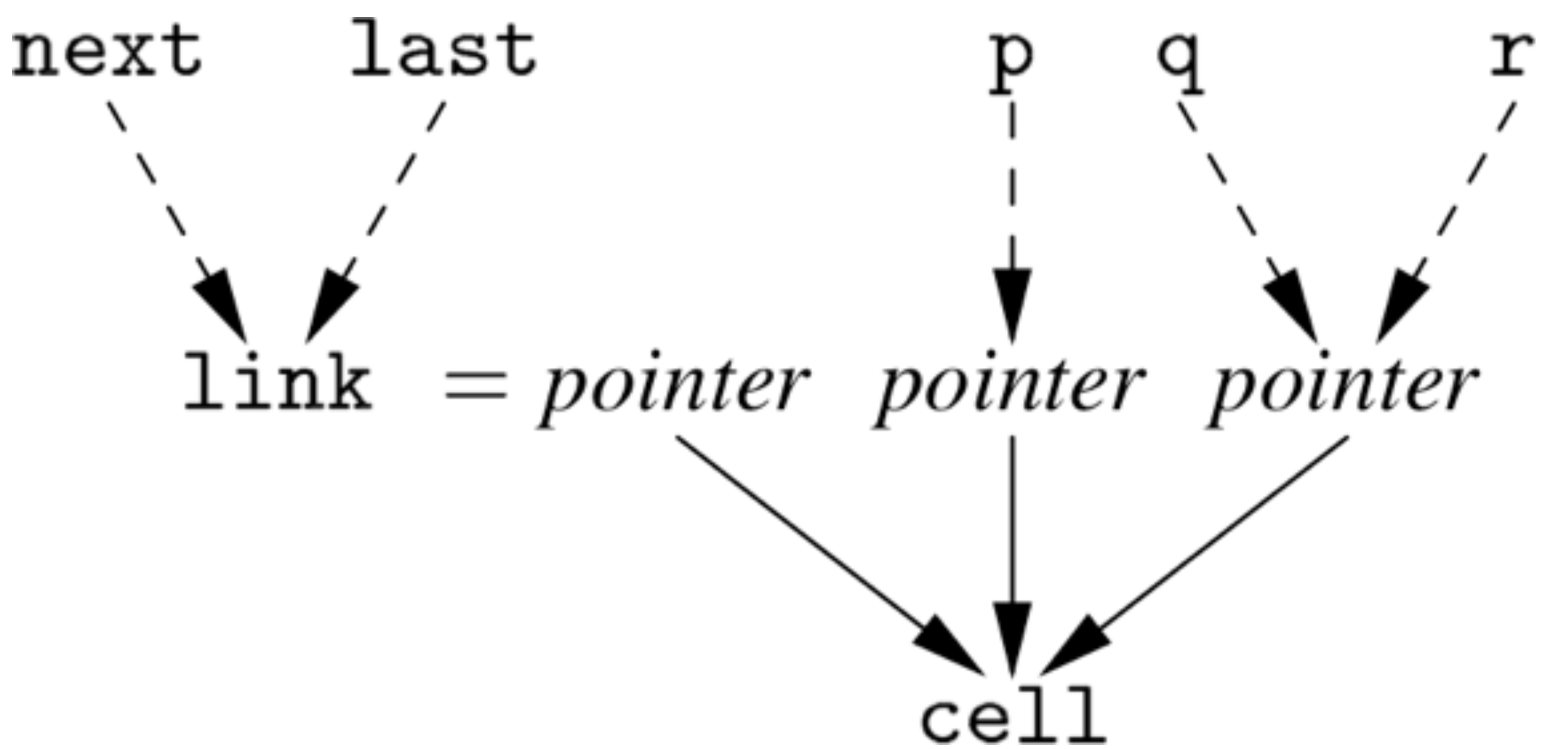
Ada/Pascal/Modula-2 are somewhat confusing: they treat distinct type definitions as distinct types, so

- `p` has different type from `q` and `r` (!)

Type compatibility: Pascal-style name equivalence

Build compile-time structure called a ***type graph***:

- each constructor or basic type creates a node
- each name creates a leaf (associated with the type's descriptor)



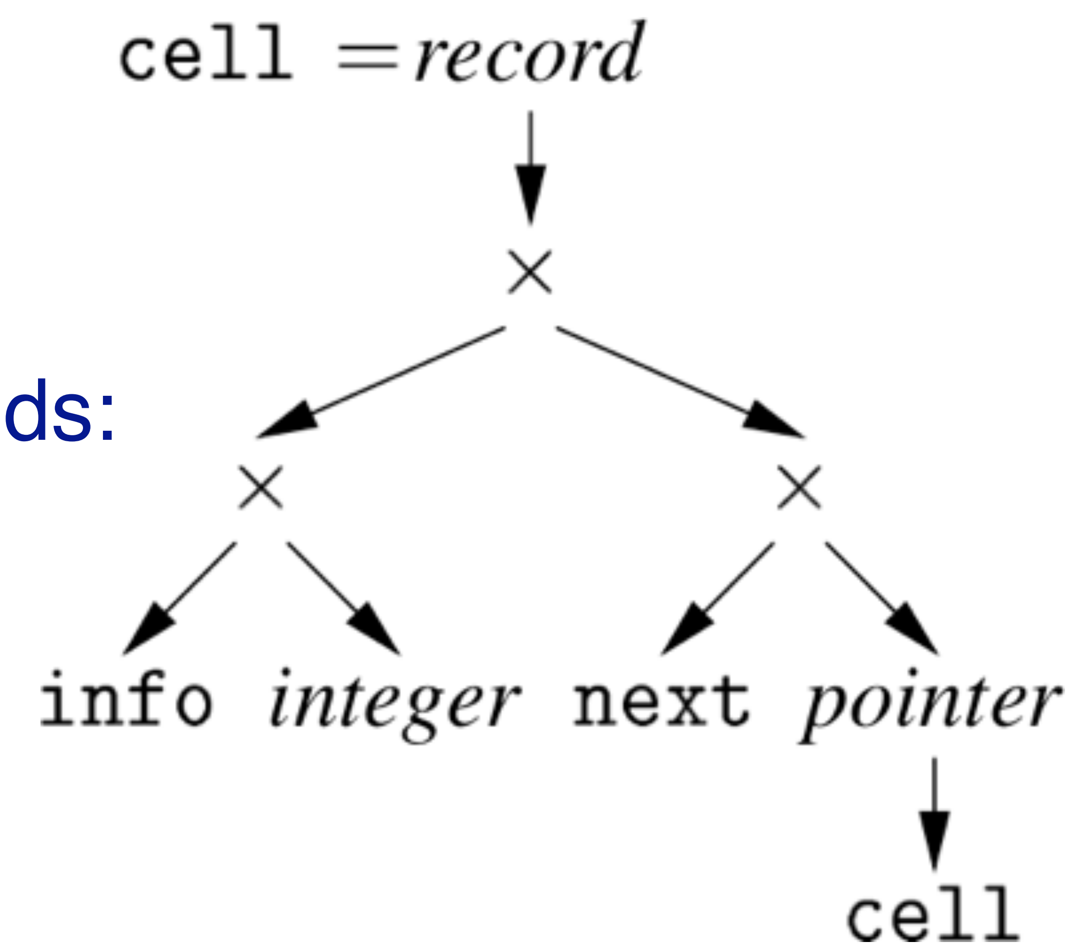
Type expressions are equivalent if they are represented by the same node in the graph

Type compatibility: recursive types

Consider:

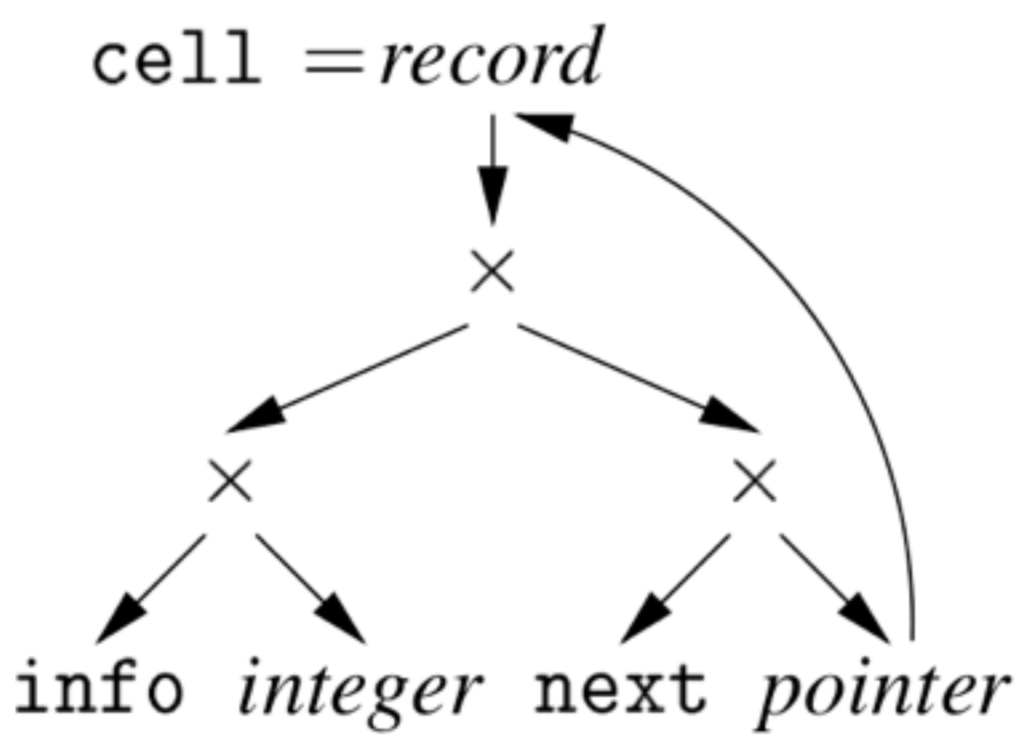
```
type link = ^cell
var cell = record
              info : integer;
              next : link;
            end
```

Expanding `link` in the type graph yields:



Type compatibility: recursive types

Allowing cycles in the type graph eliminates `cell`:



Type rules

Type-checking rules can be formalized to prove soundness and correctness.

$$\frac{f : A \rightarrow B,\ x : A}{f(x) : B}$$

If f is a function from A to B, and x is of type A, then f(x) is a value of type B.

Example: Featherweight Java

Syntax:

$$\begin{array}{lcl}
\texttt{CL} & ::= & \texttt{class C extends C } \{\overline{\texttt{C}}\ \overline{\texttt{f}}\texttt{; K } \overline{\texttt{M}}\} \\
\texttt{K} & ::= & \texttt{C(}\overline{\texttt{C}}\ \overline{\texttt{f}}\texttt{) \{super(}\overline{\texttt{f}}\texttt{); this.}\overline{\texttt{f}}\texttt{ = }\overline{\texttt{f}}\texttt{;\}} \\
\texttt{M} & ::= & \texttt{C m(}\overline{\texttt{C}}\ \overline{\texttt{x}}\texttt{) \{return e;\}} \\
\texttt{e} & ::= & \texttt{x} \\
 & | & \texttt{e.f} \\
 & | & \texttt{e.m(}\overline{\texttt{e}}\texttt{)} \\
 & | & \texttt{new C(}\overline{\texttt{e}}\texttt{)} \\
 & | & \texttt{(C)e}
\end{array}$$

Subtyping:

$$\texttt{C} <: \texttt{C}$$

$$\frac{\texttt{C} <: \texttt{D} \qquad \texttt{D} <: \texttt{E}}{\texttt{C} <: \texttt{E}}$$

$$\frac{CT(\texttt{C}) = \texttt{class C extends D \{...\}}}{\texttt{C} <: \texttt{D}}$$

Computation:

$$\frac{fields(\texttt{C}) = \overline{\texttt{C}}\ \overline{\texttt{f}}}{\texttt{(new C(}\overline{\texttt{e}}\texttt{)).f}_i \longrightarrow \texttt{e}_i} \quad \text{(R-FIELD)}$$

$$\frac{mbody(\texttt{m}, \texttt{C}) = (\overline{\texttt{x}}, \texttt{e}_0)}{\texttt{(new C(}\overline{\texttt{e}}\texttt{)).m(}\overline{\texttt{d}}\texttt{)} \longrightarrow [\overline{\texttt{d}}/\overline{\texttt{x}}, \texttt{new C(}\overline{\texttt{e}}\texttt{)/this}]\texttt{e}_0} \quad \text{(R-INVK)}$$

$$\frac{\texttt{C} <: \texttt{D}}{\texttt{(D)(new C(}\overline{\texttt{e}}\texttt{))} \longrightarrow \texttt{new C(}\overline{\texttt{e}}\texttt{)}} \quad \text{(R-CAST)}$$

Expression typing:

$$\Gamma \vdash \texttt{x} \in \Gamma(\texttt{x}) \quad \text{(T-VAR)}$$

$$\frac{\Gamma \vdash \texttt{e}_0 \in \texttt{C}_0 \qquad fields(\texttt{C}_0) = \overline{\texttt{C}}\ \overline{\texttt{f}}}{\Gamma \vdash \texttt{e}_0\texttt{.f}_i \in \texttt{C}_i} \quad \text{(T-FIELD)}$$

$$\frac{\begin{array}{c}\Gamma \vdash \texttt{e}_0 \in \texttt{C}_0 \\ mtype(\texttt{m}, \texttt{C}_0) = \overline{\texttt{D}} \rightarrow \texttt{C} \\ \Gamma \vdash \overline{\texttt{e}} \in \overline{\texttt{C}} \qquad \overline{\texttt{C}} <: \overline{\texttt{D}}\end{array}}{\Gamma \vdash \texttt{e}_0\texttt{.m(}\overline{\texttt{e}}\texttt{)} \in \texttt{C}} \quad \text{(T-INVK)}$$

$$\frac{\begin{array}{c}fields(\texttt{C}) = \overline{\texttt{D}}\ \overline{\texttt{f}} \\ \Gamma \vdash \overline{\texttt{e}} \in \overline{\texttt{C}} \qquad \overline{\texttt{C}} <: \overline{\texttt{D}}\end{array}}{\Gamma \vdash \texttt{new C(}\overline{\texttt{e}}\texttt{)} \in \texttt{C}} \quad \text{(T-NEW)}$$

$$\frac{\Gamma \vdash \texttt{e}_0 \in \texttt{D} \qquad \texttt{D} <: \texttt{C}}{\Gamma \vdash \texttt{(C)e}_0 \in \texttt{C}} \quad \text{(T-UCAST)}$$

$$\frac{\Gamma \vdash \texttt{e}_0 \in \texttt{D} \qquad \texttt{C} <: \texttt{D} \qquad \texttt{C} \neq \texttt{D}}{\Gamma \vdash \texttt{(C)e}_0 \in \texttt{C}} \quad \text{(T-DCAST)}$$

$$\frac{\begin{array}{c}\Gamma \vdash \texttt{e}_0 \in \texttt{D} \qquad \texttt{C} \not<: \texttt{D} \qquad \texttt{D} \not<: \texttt{C} \\ \textit{stupid warning}\end{array}}{\Gamma \vdash \texttt{(C)e}_0 \in \texttt{C}} \quad \text{(T-SCAST)}$$

Method typing:

$$\frac{\begin{array}{c}\overline{\texttt{x}} : \overline{\texttt{C}}, \texttt{this} : \texttt{C} \vdash \texttt{e}_0 \in \texttt{E}_0 \qquad \texttt{E}_0 <: \texttt{C}_0 \\ CT(\texttt{C}) = \texttt{class C extends D \{...\}} \\ override(\texttt{m}, \texttt{D}, \overline{\texttt{C}} \rightarrow \texttt{C}_0)\end{array}}{\texttt{C}_0\texttt{ m (}\overline{\texttt{C}}\ \overline{\texttt{x}}\texttt{) \{return e}_0\texttt{;\} OK IN C}}$$

Class typing:

$$\frac{\begin{array}{c}\texttt{K = C(}\overline{\texttt{D}}\ \overline{\texttt{g}}\texttt{, }\overline{\texttt{C}}\ \overline{\texttt{f}}\texttt{) \{super(}\overline{\texttt{g}}\texttt{); this.}\overline{\texttt{f}}\texttt{ = }\overline{\texttt{f}}\texttt{;\}} \\ fields(\texttt{D}) = \overline{\texttt{D}}\ \overline{\texttt{g}} \qquad \overline{\texttt{M}}\texttt{ OK IN C}\end{array}}{\texttt{class C extends D } \{\overline{\texttt{C}}\ \overline{\texttt{f}}\texttt{; K } \overline{\texttt{M}}\}\texttt{ OK}}$$

Used to prove that generics could be added to Java without breaking the type system.

Igarashi, Pierce and Wadler, *"Featherweight Java: a minimal core calculus for Java and GJ", OOPSLA '99*
doi.acm.org/10.1145/320384.320395

Can you answer these questions?

- ✎ Why can semantic analysis be performed by the parser?
- ✎ What are the pros and cons of introducing an IR?
- ✎ Why must an attribute dependency graph be acyclic?
- ✎ Why would be the use of a symbol table at run-time?
- ✎ Why does Java adopt nominal (name-based) rather than structural type rules?

What you should know!

- ✎ *Why is semantic analysis mostly context-sensitive?*
- ✎ *What is “peephole optimization”?*
- ✎ *Why was multi-pass semantic analysis introduced?*
- ✎ *What is an attribute grammar? How can it be used to support semantic analysis?*
- ✎ *What kind of information is stored in a symbol table?*
- ✎ *How is type-checking performed?*