198:314 Principles of Programming Languages

Course Goals

- To gain understanding of the basic structure of programming languages:
  - Data types, control structures, naming conventions,...
- To study different language paradigms:
  - Functional (*Scheme*), imperative (*C*), logic (*Prolog*), object-oriented (*C++*), parallel (*OpenMP*)
  - To ensure an appropriate language is chosen for a task
- To know the principles underlying all programming languages:
  - To make learning new programming languages easier
  - To enable *full* use of a programming language
  - To understand the implementation challenges of different programming constructs / features

Programming languages are <u>tools</u> $\Rightarrow$ understand how to design or use them

Course Information

Prerequisites (summary):

- CS 205 (Introduction to Discrete Structures)
- CS 211 (Computer Architecture)

Important facts:

staff:	Prof. Ulrich Kremer, Hans Christian Woithe, Liu Liu, Ardash Yoga
lectures:	Tu/Fri noon-1:20pm, TIL-254 (Tillett Hall)
recitations:	**attendance mandatory, start this Friday**
	section 1, Tu 1:55-2:50pm, LCB 110
	section 2, Tu 5:15-6:10pm, TIL-103A
	section 3, Fri 1:55-2:50pm, TIL-251
books on: reserve	Science & Engineering Resource Center (SEC), Busch Campus

Basis for grades (subject to changes):

10%	homework / recitation
25%	mid-term exam
35%	final exam (cumulative)
30%	three major programming projects

Course Information (Cont.)

- The textbook for this course is *" Programming Language Pragmatics* by Michael L. Scott, 3nd Edition, Morgan Kaufmann (Elsevier), 2009.
- Additional (recommended) texts: see course web page

Course material is available on our class website at

www.cs.rutgers.edu/courses/314/classes/spring_2014_kremer

In addition, there is a news group (sakai web page) sakai.rutgers.edu. All questions regarding homeworks and projects should be posted here. **YOU SHOULD READ THE SAKAI NEWS GROUP AND LOOK AT THE HOME PAGE AT LEAST EVERY OTHER DAY**

All programming will be done on the ilab cluster. Get yourself an ilab account (see link on bottom of our 314 website). Learn to do the normal things — edit, compile, ...

Course Information (Cont.)

$\boxed{\textbf{Academic Integrity}}$ (see our web page)

→ read-protect your directories and files (ilab)

→ no group projects

→ will use MOSS for detecting software plagiarism

14 weeks, no "make-up" work after the end of the course. If there is a problem, let me know immediately.

IMPORTANT INFORMATION ⇒ will be posted on 314 web page and/or on sakai forums!

- Failure to take a scheduled exam
- Grading of homeworks and projects
- Instructions of how to submit programming projects
- Partial credit for late project submissions

Email TAs or me:

- **Subject line** has to start with **314:**, e.g., *314: Question about my midterm exam*
- **No** project and homework questions; post them on the sakai discussion forums;

Course Information (Cont.)

Special permission numbers

- Put your name (and email address!) on the list.
  Indicate whether you prefer any particular section.
- Come talk to me after class.
- Will try to accommodate everyone.

Course Information (Cont.)

$\boxed{\text{I use overhead transparencies}}$

- I try to moderate my speed
- *You* need to say STOP!
- all transparencies are on the Web (PDF)
- you should still take some notes

$\boxed{\text{I'll tell you where we are in the book}}$

- I don't lecture directly from the book
- *You* need to read the book
- Going to the recitations is mandatory
- I strongly recommend coming to the lectures

What is the Purpose of a Programming Language?

A programming language is ...

> a set of conventions for communicating an algorithm. *Horowitz*

Purposes:

- specifying algorithm and data structures
- communicating algorithms among people
- establishing correctness (allow reasoning)

Why Use Anything Besides Machine Code?

This is a C program that uses two one-dimensional arrays **a** and **b** of size **SIZE**. The arrays are initialized, and then a sum reduction is performed. The size of the arrays and the result of the sum reduction is printed out.

example.c

```
#include <stdio.h>

#define SIZE 100
int main() {
  int a[SIZE], b[SIZE];
  int i, sum;

  for (i=0; i<SIZE; i++) {
    a[i] = 1;
    b[i] = 2;
  }
  sum = 0;
  for (i=0; i<SIZE; i++)
    sum = sum + a[i] + b[i];

  printf("for two arrays of size %d, sum = %d\n", SIZE, sum);
}
```

Why Use Anything Besides Machine Code?

Compiler: gcc -O3 -S example.c ⇒ example.s

```
.file "example.c"
.version "01.01"
gcc2_compiled.:
.section .rodata.str1.32,"aMS",@progbits,1
.align 32
.LC0:
.string "for two arrays of size %d, sum = %d\n"
.text
.align 4
.globl main
.type  main,@function
main:
pushl %ebp
movl %esp, %ebp
xorl %eax, %eax
subl $808, %esp
movl $99, %edx
.p2align 2
.L21:
movl $1, -408(%ebp,%eax)
movl $2, -808(%ebp,%eax)
addl $4, %eax
decl %edx
jns .L21
xorl %ecx, %ecx
xorl %eax, %eax
movl $99, %edx
.p2align 2
.L26:
addl -408(%ebp,%eax), %ecx
addl -808(%ebp,%eax), %ecx
addl $4, %eax
decl %edx
jns .L26
pushl %eax
pushl %ecx
pushl $100
pushl $.LC0
call printf
addl $16, %esp
leave
ret
.Lfe1:
.size  main,.Lfe1-main
.ident "GCC: (GNU) 2.96 20000731 (Red Hat Linux 7.3 2.96-112)"
```

Why Use Anything Besides Machine Code?

gcc -o example.o -O3 example.c; strip example.o; objdump -d example.o

```
objdump: example.o: No symbols

example.o:     file format elf32-sparc

Disassembly of section .text:

00010444 <.text>:
   10444: bc 10 20 00  clr  %fp
   10448: e0 03 a0 40  ld  [ %sp + 0x40 ], %l0
   1044c: a2 03 a0 44  add  %sp, 0x44, %l1
   10450: 9c 23 a0 20  sub  %sp, 0x20, %sp
   10454: 80 90 00 01  tst  %g1
   10458: 02 80 00 04  be  0x10468
   1045c: 90 10 00 01  mov  %g1, %o0
   10460: 40 00 40 c4  call  0x20770
   10464: 01 00 00 00  nop
   10468: 11 00 00 41  sethi  %hi(0x10400), %o0
   1046c: 90 12 22 d8  or  %o0, 0x2d8, %o0 ! 0x106d8
   10470: 40 00 40 c0  call  0x20770
   10474: 01 00 00 00  nop
   10478: 40 00 00 91  call  0x106bc
   1047c: 01 00 00 00  nop
   10480: 90 10 00 10  mov  %l0, %o0
   10484: 92 10 00 11  mov  %l1, %o1
   10488: 95 2c 20 02  sll  %l0, 2, %o2
   1048c: 94 02 a0 04  add  %o2, 4, %o2
   10490: 94 04 40 0a  add  %l1, %o2, %o2
   10494: 17 00 00 82  sethi  %hi(0x20800), %o3
   10498: 96 12 e0 a8  or  %o3, 0xa8, %o3 ! 0x208a8
   1049c: d4 22 c0 00  st  %o2, [ %o3 ]
   104a0: 40 00 00 4e  call  0x105d8
   104a4: 01 00 00 00  nop
   104a8: 40 00 40 b5  call  0x2077c
   104ac: 01 00 00 00  nop
   104b0: 40 00 40 b6  call  0x20788
   104b4: 01 00 00 00  nop
   104b8: 81 c3 e0 08  retl
   104bc: ae 03 c0 17  add  %o7, %l7, %l7
   104c0: 9d e3 bf 90  save  %sp, -112, %sp
   104c4: 11 00 00 00  sethi  %hi(0), %o0
   104c8: 2f 00 00 40  sethi  %hi(0x10000), %l7
   104cc: 7f ff ff fb  call  0x104b8
   104d0: ae 05 e2 54  add  %l7, 0x254, %l7 ! 0x10254
   104d4: 90 12 20 0c  or  %o0, 0xc, %o0
   104d8: d2 05 c0 08  ld  [ %l7 + %o0 ], %o1
   104dc: d4 02 40 00  ld  [ %o1 ], %o2
   104e0: 80 a2 a0 00  cmp  %o2, 0
   104e4: 12 80 00 23  bne  0x10570
   104e8: 11 00 00 00  sethi  %hi(0), %o0
   104ec: 90 12 20 10  or  %o0, 0x10, %o0 ! 0x10
   104f0: d4 05 c0 08  ld  [ %l7 + %o0 ], %o2
   104f4: d2 02 80 00  ld  [ %o2 ], %o1
   104f8: d0 02 40 00  ld  [ %o1 ], %o0
   104fc: 80 a2 20 00  cmp  %o0, 0
   10500: 02 80 00 0f  be  0x1053c
   10504: 11 00 00 00  sethi  %hi(0), %o0
   10508: a0 10 00 0a  mov  %o2, %l0
   1050c: d0 04 00 00  ld  [ %l0 ], %o0
   10510: 90 02 20 04  add  %o0, 4, %o0
   10514: d0 24 00 00  st  %o0, [ %l0 ]
   10518: d2 02 3f fc  ld  [ %o0 + -4 ], %o1
   1051c: 9f c2 40 00  call  %o1
   10520: 01 00 00 00  nop
   10524: d0 04 00 00  ld  [ %l0 ], %o0
   10528: d2 02 00 00  ld  [ %o0 ], %o1
   1052c: 80 a2 60 00  cmp  %o1, 0
   10530: 12 bf ff f9  bne  0x10514
   10534: 90 02 20 04  add  %o0, 4, %o0
   10538: 11 00 00 00  sethi  %hi(0), %o0
   1053c: 90 12 20 1c  or  %o0, 0x1c, %o0 ! 0x1c
   10540: d2 05 c0 08  ld  [ %l7 + %o0 ], %o1
   10544: 80 a2 60 00  cmp  %o1, 0
   10548: 02 80 00 05  be  0x1055c
```

```
1054c: 13 00 00 00  sethi  %hi(0), %o1
10550: 92 12 60 08  or  %o1, 8, %o1 ! 0x8
10554: 40 00 40 90  call  0x20794
10558: d0 05 c0 09  ld  [ %l7 + %o1 ], %o0
1055c: 11 00 00 00  sethi  %hi(0), %o0
10560: 90 12 20 0c  or  %o0, 0xc, %o0 ! 0xc
10564: d4 05 c0 08  ld  [ %l7 + %o0 ], %o2
10568: 92 10 20 01  mov  1, %o1
1056c: d2 22 80 00  st  %o1, [ %o2 ]
10570: 81 c7 e0 08  ret
10574: 81 e8 00 00  restore
10578: 9d e3 bf 90  save  %sp, -112, %sp
1057c: 81 c7 e0 08  ret
10580: 81 e8 00 00  restore
10584: 9d e3 bf 90  save  %sp, -112, %sp
10588: 11 00 00 00  sethi  %hi(0), %o0
1058c: 2f 00 00 40  sethi  %hi(0x10000), %l7
10590: 7f ff ff ca  call  0x104b8
10594: ae 05 e1 90  add  %l7, 0x190, %l7 ! 0x10190
10598: 90 12 20 18  or  %o0, 0x18, %o0
1059c: d2 05 c0 08  ld  [ %l7 + %o0 ], %o1
105a0: 80 a2 60 00  cmp  %o1, 0
105a4: 02 80 00 08  be  0x105c4
105a8: 13 00 00 00  sethi  %hi(0), %o1
105ac: 92 12 60 08  or  %o1, 8, %o1 ! 0x8
105b0: 15 00 00 00  sethi  %hi(0), %o2
105b4: d0 05 c0 09  ld  [ %l7 + %o1 ], %o0
105b8: 94 12 a0 04  or  %o2, 4, %o2
105bc: 40 00 40 79  call  0x207a0
105c0: d2 05 c0 0a  ld  [ %l7 + %o2 ], %o1
105c4: 81 c7 e0 08  ret
105c8: 81 e8 00 00  restore
105cc: 9d e3 bf 90  save  %sp, -112, %sp
105d0: 81 c7 e0 08  ret
105d4: 81 e8 00 00  restore
105d8: 9d e3 bc 70  save  %sp, -912, %sp
105dc: 92 07 be 60  add  %fp, -416, %o1
105e0: 94 07 bc d0  add  %fp, -816, %o2
105e4: 86 10 00 09  mov  %o1, %g3
105e8: 84 10 00 0a  mov  %o2, %g2
105ec: 9a 10 20 01  mov  1, %o5
105f0: 98 10 20 02  mov  2, %o4
105f4: 90 10 20 00  clr  %o0
105f8: 96 10 20 63  mov  0x63, %o3
105fc: da 22 00 03  st  %o5, [ %o0 + %g3 ]
10600: d8 22 00 02  st  %o4, [ %o0 + %g2 ]
10604: 96 82 ff ff  addcc  %o3, -1, %o3
10608: 1c bf ff fd  bpos  0x105fc
1060c: 90 02 20 04  add  %o0, 4, %o0
10610: 9a 10 00 0a  mov  %o2, %o5
10614: 84 10 00 09  mov  %o1, %g2
10618: 94 10 20 00  clr  %o2
1061c: 98 10 20 00  clr  %o4
10620: 96 10 20 63  mov  0x63, %o3
10624: d0 03 00 02  ld  [ %o4 + %g2 ], %o0
10628: 96 82 ff ff  addcc  %o3, -1, %o3
1062c: d2 03 00 0d  ld  [ %o4 + %o5 ], %o1
10630: 90 02 80 08  add  %o2, %o0, %o0
10634: 94 02 00 09  add  %o0, %o1, %o2
10638: 1c bf ff fb  bpos  0x10624
1063c: 98 03 20 04  add  %o4, 4, %o4
10640: 11 00 00 41  sethi  %hi(0x10400), %o0
10644: 90 12 22 f8  or  %o0, 0x2f8, %o0 ! 0x106f8
10648: 40 00 40 59  call  0x207ac
1064c: 92 10 20 64  mov  0x64, %o1
10650: 81 c7 e0 08  ret
10654: 81 e8 00 00  restore
10658: 81 c3 e0 08  retl
1065c: ae 03 c0 17  add  %o7, %l7, %l7
10660: 9d e3 bf 90  save  %sp, -112, %sp
10664: 11 00 00 00  sethi  %hi(0), %o0
10668: 2f 00 00 40  sethi  %hi(0x10000), %l7
1066c: 7f ff ff fb  call  0x10658
10670: ae 05 e0 b4  add  %l7, 0xb4, %l7 ! 0x100b4
10674: 90 12 20 14  or  %o0, 0x14, %o0
10678: d2 05 c0 08  ld  [ %l7 + %o0 ], %o1
1067c: d4 02 7f fc  ld  [ %o1 + -4 ], %o2
10680: 80 a2 bf ff  cmp  %o2, -1
10684: 02 80 00 09  be  0x106a8
10688: a0 02 7f fc  add  %o1, -4, %l0
1068c: d0 04 00 00  ld  [ %l0 ], %o0
10690: 9f c2 00 00  call  %o0
10694: a0 04 3f fc  add  %l0, -4, %l0
```

```
   10698: d0 04 00 00  ld  [ %l0 ], %o0
   1069c: 80 a2 3f ff  cmp  %o0, -1
   106a0: 12 bf ff fb  bne  0x1068c
   106a4: 01 00 00 00  nop
   106a8: 81 c7 e0 08  ret
   106ac: 81 e8 00 00  restore
   106b0: 9d e3 bf 90  save  %sp, -112, %sp
   106b4: 81 c7 e0 08  ret
   106b8: 81 e8 00 00  restore
Disassembly of section .init:

000106bc <.init>:
   106bc: 9d e3 bf a0  save  %sp, -96, %sp
   106c0: 7f ff ff b1  call  0x10584
   106c4: 01 00 00 00  nop
   106c8: 7f ff ff e6  call  0x10660
   106cc: 01 00 00 00  nop
   106d0: 81 c7 e0 08  ret
   106d4: 81 e8 00 00  restore
Disassembly of section .fini:

000106d8 <.fini>:
   106d8: 9d e3 bf a0  save  %sp, -96, %sp
   106dc: 7f ff ff 79  call  0x104c0
   106e0: 01 00 00 00  nop
   106e4: 81 c7 e0 08  ret
   106e8: 81 e8 00 00  restore
Disassembly of section .plt:

00020740 <.plt>:
...
   20770: 03 00 00 30  sethi  %hi(0xc000), %g1
   20774: 30 bf ff f3  b,a   0x20740
   20778: 01 00 00 00  nop
   2077c: 03 00 00 3c  sethi  %hi(0xf000), %g1
   20780: 30 bf ff f0  b,a   0x20740
   20784: 01 00 00 00  nop
   20788: 03 00 00 48  sethi  %hi(0x12000), %g1
   2078c: 30 bf ff ed  b,a   0x20740
   20790: 01 00 00 00  nop
   20794: 03 00 00 54  sethi  %hi(0x15000), %g1
   20798: 30 bf ff ea  b,a   0x20740
   2079c: 01 00 00 00  nop
   207a0: 03 00 00 60  sethi  %hi(0x18000), %g1
   207a4: 30 bf ff e7  b,a   0x20740
   207a8: 01 00 00 00  nop
   207ac: 03 00 00 6c  sethi  %hi(0x1b000), %g1
   207b0: 30 bf ff e4  b,a   0x20740
   207b4: 01 00 00 00  nop
   207b8: 01 00 00 00  nop
```

Why Use Anything Besides Machine Code?

Need for high-level programming languages for

- Readable, familiar notations
- Machine independence (portability)
- Consistency checks during implementation
- Dealing with scale

  The art of programming is the art of organizing complexity. Example: *Dijkstra, 1972*

However:

- Acceptable loss of efficiency

  First FORTRAN compiler built by IBM, in 1957, translated into code as efficient as hand-coded code. *John Backus*

Why Learn More than One Programming Language?

- Each language encourages thinking about a problem in a particular way.
- Each language provides (slightly) different expressiveness & efficiency.

$\Rightarrow$ The language should match the problem.

Why Learn About Programming Language PRINCIPLES?

A programming language is a **tool**.

Studying the design of a tool leads to:

- Better understanding of its functionality and limitations.
- Increased competence in using it.
- Basis for lots of other work in computer science.

Computational Paradigms

Imperative:

Sequence of state-changing actions.

- Manipulate an abstract machine with:
  1. Variables naming memory locations
  2. Arithmetic and logical operations
  3. Reference, evaluate, assign operations
  4. Explicit control flow statements
- Fits the von Neumann architecture closely
- Key operations: *Assignment* and "*Goto*"

Functional:

Composition of operations on data.

- No named memory locations
- Value binding through parameter passing
- Key operations: *Function application* and *Function abstraction*

Basis in lambda calculus

Computational Paradigms (Cont.)

Logic:

Formal logic specification of problem.

- Programs say *what* properties the solution must have, not *how* to find it
- Solutions through reasoning process.
- Key operation: *Unification*

Basis in first order predicate logic

Object-Oriented:

Communication between abstract objects.

- "Objects" collect both the data and the operations
- "Objects" provide *data abstraction*
- Can be either imperative or functional
- Key operation: *Message passing or Method invocation*

Computational Paradigms (Cont.)

Event-Driven:

Objects are associated with events

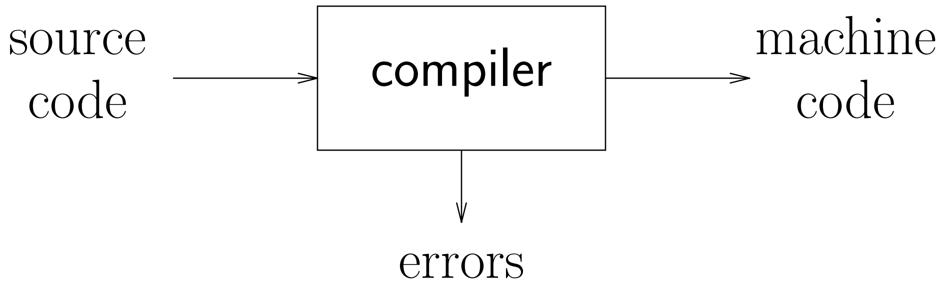
- events are asynchronous
- arrival of an event triggers action
- main applications: GUI, simulations
- Key operation: *event handling*

Parallel:

Computations and data accesses at the same time

- functional (task/threads) and data parallelism
- different granularities: instruction, loop, or task level
- synchronization: locks, message passing, . . .
- Key notions: *control and data dependencies*

Compilers



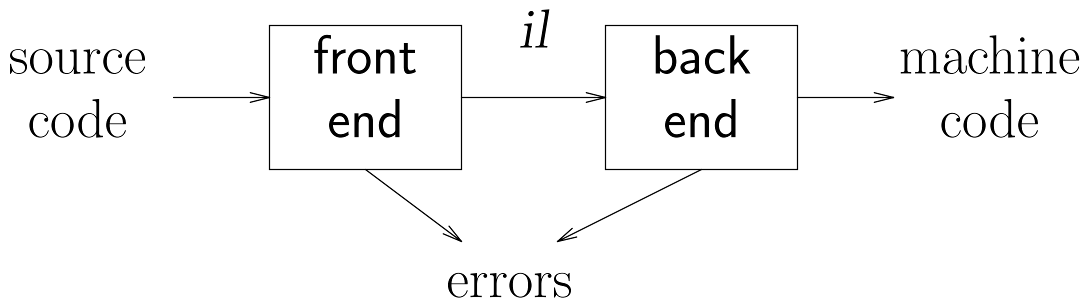
Implications:

- recognize legal (and illegal) programs
- generate correct code
- manage storage of all variables and code
- need format for object (or assembly) code

Big step up from assembler – higher level notations

Traditional two pass compiler

Pass: reading and writing entire program



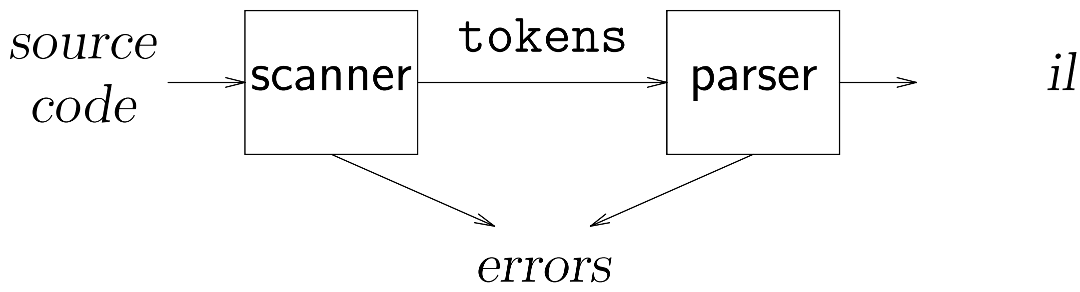
Implications:

- intermediate language (*il*)
- front end maps legal code into *il*
- back end maps *il* onto target machine
- simplify retargeting
- allows multiple front ends
- multiple passes $\Rightarrow$ better code

Front end is $\mathbf{O}(\mathrm{n})$

Back end is NP-Complete

Front end



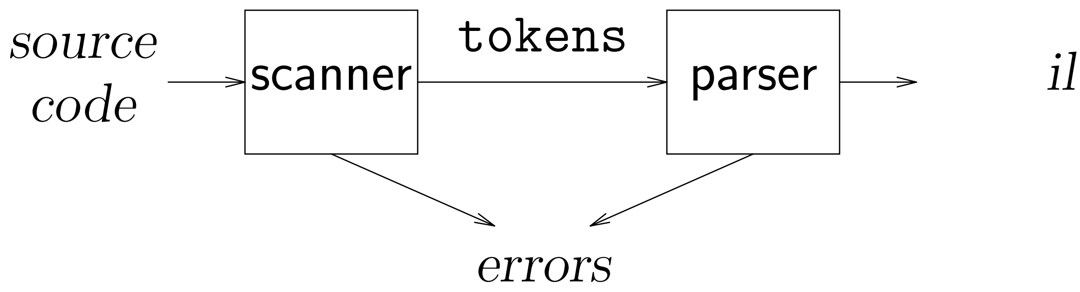
Parser: *syntax & semantic analyzer, il code generator (syntax-directed translator)*

Front End Responsibilities:

- *recognize legal programs*
- *report errors*
- *produce il*
- *preliminary storage map*
- *shape the code for the back end*

Much of front end construction can be automated

Scanner



Scanner

- *maps characters into tokens – the basic unit of syntax*

  `x = x + y;`

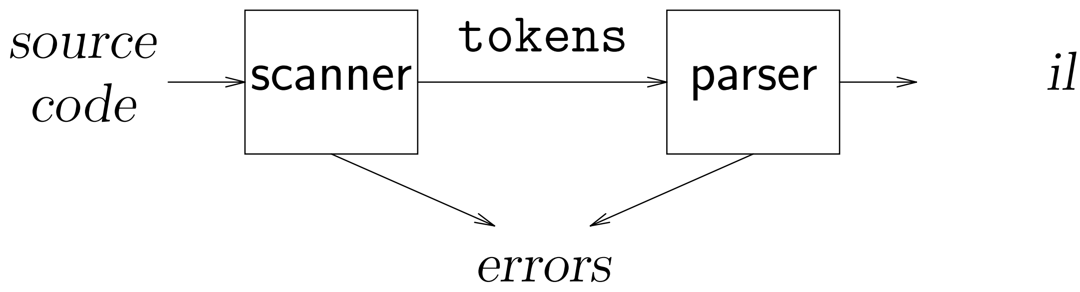
  becomes

  <*id*, `x`> `=` <*id*, `x`> `+` <*id*, `y`> `;`

- *character string for a token is a lexeme*
- *typical tokens: number, id,* `+`, `-`, `*`, `/`, `do`, `end`
- *eliminates white space (tabs, blanks, comments)*
- *a key issue is speed*

  ⇒ *use specialized recognizer* (`lex`)

Parser



Parser:

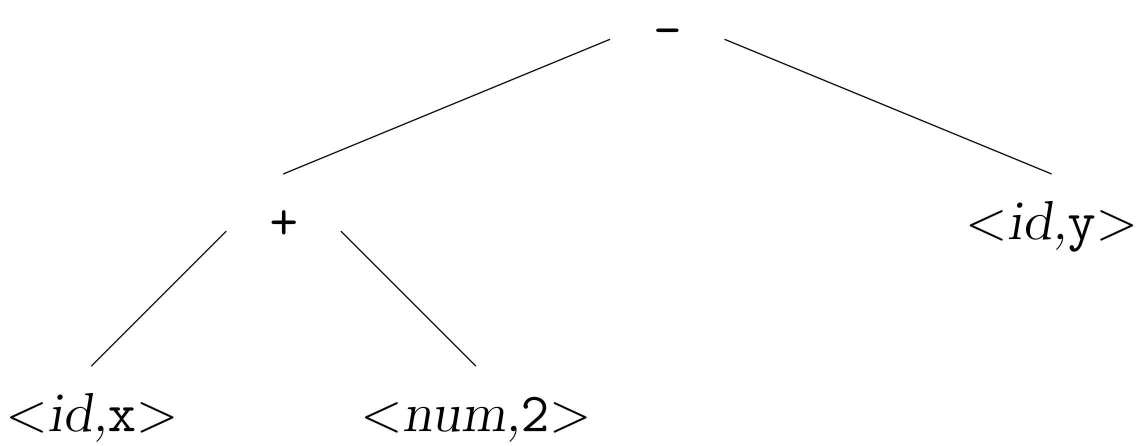
- *recognize context-free syntax (Context Free Grammars)*
- *guide context-sensitive analysis*
- *construct il(s)*
- *produce meaningful error messages*
- *attempt error correction*

Parser generators mechanize much of the work

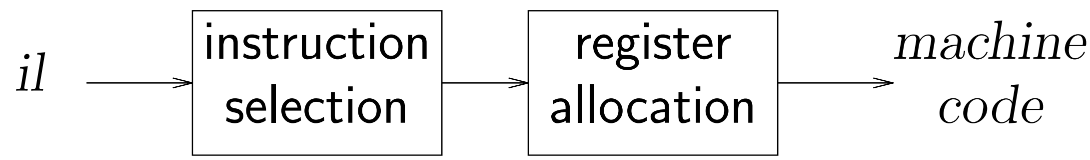
Example *il*: Abstract syntax tree (AST)

Compilers often use an abstract syntax tree.

$\boxed{x + 2 - y}$



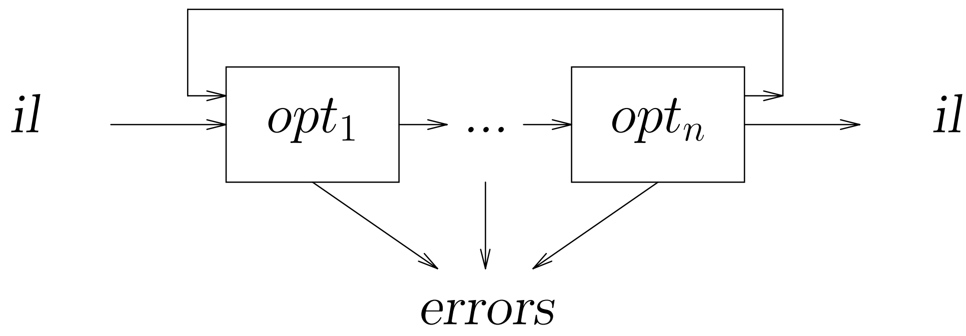
Back end



Responsibilities

- *translate il into target machine code*
- *choose instructions for each il operation*
- *decide what to keep in registers at each point*

Optimizer (middle end)



Modern optimizers are usually built as a set of passes.

Typical passes

- *discover & propagate constant values*
- *reduction of operator strength*
- *common subexpression elimination*
- *redundant computation elimination*
- *encode an idiom in some powerful instruction*
- *move computation to less frequently executed place* (e.g., *out of loops)*

Things to Do

Things to do for next lecture:

- *read Scott: Chapter 1 (covers today's lecture)*
- *read Scott: Chapters 2.1 and 2.2; ALSU: Chapters 3.1 - 3.4*
- *get an ilab account*
- *learn to read Sakai news group*

Recitations will start **this Friday (section 3)**.