CS421 Compilers and Interpreters

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Course Structure

- *Course home page:* **http://flint.cs.yale.edu/cs421**

  all lecture notes and other course-related information are available on this class home page.

- *13-week lectures (based on Appel book + Ullman book + other)*

  compiler basics, internals, algorithms, and advanced topics, etc.

- *7 programming assignments*

  *build a compiler compiling **Tiger** progs into the X86 assembly code.*

- *Occasional problem sets plus a final exam*
- *Use the SML/NJ environment on the Zoo Linux PCs*

Why Study Compilers?

or why take CS421 ?

- *To enhance understanding of programming languages*
- *To have an in-depths knowledge of low-level machine executables*
- *To write compilers and interpreters for various programming languages and domain-specific languages*

  Examples: Java, JavaScript, C, C++, C#, Modula-3, Scheme, ML, Tcl/Tk, Database Query Lang., Mathematica, Matlab, Shell-Command-Languages, Awk, Perl, your .mailrc file, HTML, TeX, PostScript, Kermit scripts, ...

- *To learn various system-building tools : Lex, Yacc, ...*
- *To learn interesting compiler theory and algorithms.*
- *To learn the beauty of programming in modern programming lang.*

Systems Environments

- *To become a **real** computer professional, you must not only know how to write good programs, but also know how programs are compiled and executed on different machines.*
- ***Core Systems Environments** include: programming languages, compilers, computer architectures, and operating systems*

  1. a language for you to express what to do
  2. a translator that translates what you say to what machine knows
  3. an execution engine to execute the actions
  4. a friendly operating environment that connects all the devices

- ***Application Systems Environments** include: distributed systems, computer networks, parallel computations, database systems, computer graphics, multimedia systems.*

Compilers are Translators

Table 1: various forms of translators

L	*L'*	*translator*
C++, ML, Java	assembly/machine code	compiler
assembly lang.	machine code	assembler
"object" code (*.o file)	"executable" code (a.out)	linker/loader
macros/text	text	macro processor (cpp)
troff/Tex/HTML	PostScript	document formatter
any file (e.g., foo)	compressed file (foo.Z)	file compresser

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Compilers and Interpreters

*Given a program **P** written in language **L**,*

- *A **compiler** is simply a translator; compiling a program **P** returns the corresponding machine code (e.g., Power PC) for **P***
- *An **interpreter** is a translator plus a virtual machine engine; interpreting a program **P** means translating **P** into the virtual machine code **M** and then executing **M** upon the virtual machine and return the result.*

In summary, we will focus on the following:

- *how to write a translator ?*
- *what are the possible source languages and target languages ?*
- *what are the possible physical or virtual machine architectures ?*
- *(a little bit on) why does the translation preserve the semantic meaning?*

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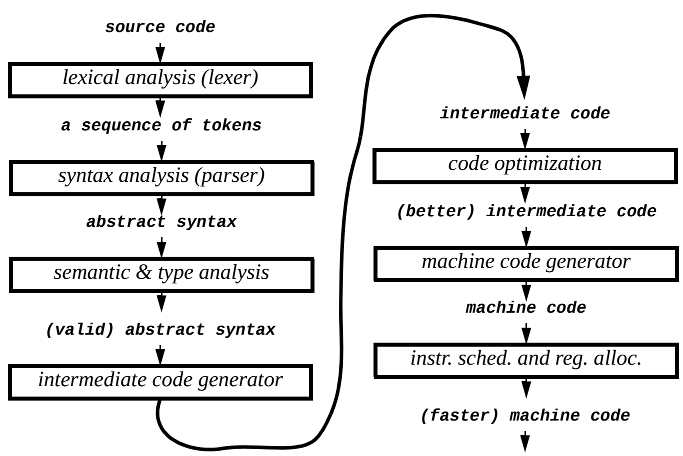
Compilation Phases



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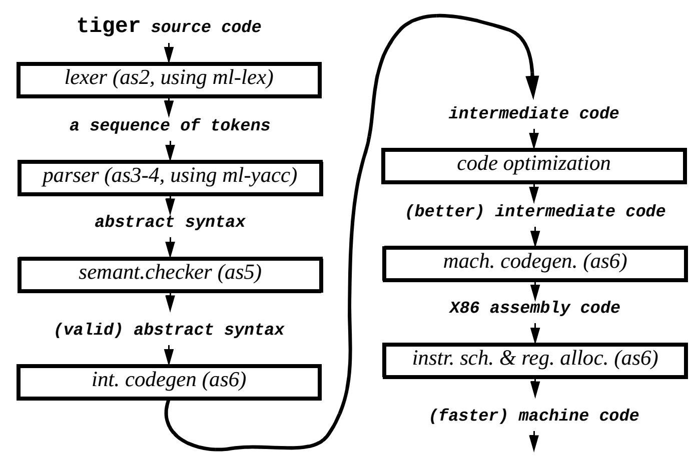
Programming Assignments



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An Example of *Tiger*

```
(* A program to solve the 8-queens problem, see Appel's book *)

let
    var N := 8

    type intArray = array int
    var row := intArray [ N ] of 0
    var col := intArray [ N ] of 0
    var diag1 := intArray [N+N-1] of 0
    var diag2 := intArray [N+N-1] of 0

    function printboard() =
       (for i := 0 to N-1
        do (for j := 0 to N-1
            do print(if col[i]=j then " O" else " .");
            print("\n"));
        print("\n"))

    function try(c:int) =
      (* for i:= 0 to c do print("."); print("\n"); flush(); *)
      if c=N then printboard()
      else for r := 0 to N-1
           do if row[r]=0 & diag1[r+c]=0 & diag2[r+7-c]=0
              then (row[r]:=1; diag1[r+c]:=1; diag2[r+7-c]:=1;
                    col[c]:=r; try(c+1);
                    row[r]:=0; diag1[r+c]:=0; diag2[r+7-c]:=0)

 in try(0)
end
```

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Using the SML/NJ compiler

- *Add* `/c/cs421/bin` *to the front of your PATH variable*
- *Type* `sml` *to run the SML/NJ compiler (used in assignment 1)*
- *Type* `CM.make "sources.cm";` *to run the separate compilation system (the makefile is called* `sources.cm`*, used in as2 -- as7)*
- `Ctrl-d` *exits the compiler;* `Ctrl-c` *breaks the exectution;* `Ctrl-z` *stops the execution as normal Unix programs*
- *Three ways to run ML programs: (1) type in your code in the interactive prompt inside **sml;** (2) edit your ML code in a file, say,* `foo.sml`*; then inside **sml**, type* `use "foo.sml";` *(3) use the separate compilation system**;***
- *The directory **/c/cs421/as** contains all the files needed for doing all 7 programming assignments in Appel's book.*

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Why Standard ML ?

- *Efficiency*
- *Safety and simplicity*
- *Statically-typed*
- *Powerful module system*
- *Garbage collection (automatic memory management)*
- *Low-level systems programming support*
- *Higher-order functions*
- *Polymorphism*
- *Other features: formal definitions, type inference, value-oriented prog.*

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ML Tutorial

- *Integers :* `3, 54` *;* *Negative Integers:* `~3, ~54`
- *Reals:* `3.0,3.14, ~3.32E~7` *;*
- *Overloaded arithmetic operators :* `+, -, *, /, <, >, <=, >`
- *Boolean :* `true, false` *; operators:* `andalso, orelse, not`
- *Strings :* `"hello world\n", "yale university", ...`
- *Lists :* `[], 3::4::nil, [2,3], ["freshman", "senior"], ...`
- *Expressions: constant, list expr, cond. expr, let expr, function application*
- *Declarations:*

value binding :

```
val x = 3;
val y = x + x;
```

function-value binding :

```
fun fac n = if n=0 then 1
            else n*(fac(n-1));
```

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ML Tutorial (cont'd)

- ***Function values***

The expression "**fn** *var* **=>** *exp*" denotes the function with formal parameter `var` and body `exp`. The **fn** is pronounced "lambda".

examples: **val** f = **fn** x => (**fn** y => (x+y+3))
it is equivalent to **fun** f x y = x+y+3

- ***Constructed values***

pair and tuple : (3, 4.5), ("email", 4.5+x, true)

records: {lab1 = exp1, ... , labn = expn} (n>=0)
examples: {make = "Ford", built = 1904}

unit: denoted as `()`, used to represent 0-tuple or empty record `{}`

ML Tutorial (cont'd)

- ***Extract the n-th field of a n-tuple***

```
val x = (3,4.5,"hello")
val y = #1(x)
val z = #3(x)
```

- ***Extract a specific field of a record***

```
val car = {make = "Ford", year=1984}
val m = #make(car)
val y = #year(car)
```


ML Tutorial (cont'd)

- ***Patterns*** --- *a form to decompose constructed values, commonly used in value binding and function-value binding.*

```
val pat = exp              fun var(pat) = exp

variable pattern:      val x = 3
                       fun f(y) = x+y+2

pattern for pairs, tuples, and records:

       val pair = (3,4)
       val (x,y) = pair
       val car = {make = "Ford", built=1904}
       fun modernize{make = m, built = year} =
              {make = m, built = year+1}

wildcard pattern: _        unit pattern: ()
constant pattern: 3, 4.5   constructor pattern: []
```


ML Tutorial (cont'd)

- ***Pattern Matching ---***

A **match rule** `pat => exp`

A **match** is a set of match rules
$pat_1 => exp_1$ | ... | $pat_n => exp_n$

When a match is applied to a value, `v`; we search from left to right, look for the first match rule whose pattern matches `v`.

the case expression : **case** exp **of** match

the function expression: **fn** match

the function-value binding:

```
fun var pat1 = exp1
  | var pat2 = exp2
     ......
  | var patn = expn
```

ML Tutorial (cont'd)

- ***Pattern Matching Examples:***

```
fun length l = case l
                of [] => 0
                 | [a] => 1
                 | _::r => 1 + (length r)

fun length [] = 0
  | length [a] = 1
  | length (_::r) = 1 + (length r)


fun even 0 = true
  | even n = odd(n-1)

and odd 0 = false
  | odd n = even(n-1)
```

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ML Tutorial (cont'd)

- ***Type Expressions***

```
int, bool, real, string, int list, t1*t2, t1->t2

x : int
fac : int -> int
f : int -> int -> int
modernize : {make : string, build : int} ->
                {make : string, build : int}
length : 'a list -> int
(3,4.0) : int * real
```

- ***Type Abbreviations***

```
type tycon = ty

Examples:    type car = {make : string, built : int}
             type point = real * real
             type line = point * point
```

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ML Tutorial (cont'd)

- ***Datatype declarations:***

```
datatype tycon = con1 of ty1
               | con2 of ty2
                ......
                | conn of tyn
```

This declares a new type, called "`tycon`" with n value constructors `con1 ,..., conn.` The "`of tyi`" can be omitted if `coni` is nullary.

Examples: `datatype color = RED | GREEN | BLUE`

this introduces a new type `color` and 3 new value constructors `RED, GREEN,` and `BLUE,` all have type `color.` A value constructor can be used both as a value and as a pattern, e.g.,

```
fun swap(RED) = GREEN
  | swap(GREEN) = BLUE
  | swap(BLUE) = RED
```

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ML Tutorial (cont'd)

- ***Datatype declaration example :***

```
datatype 'a list = nil
                 | :: of 'a * 'a list

fun map f [] = []
  | map f (a::r) = (f a)::(map f r)

fun rev l = let fun h([], r) = r
                  | h(a::z, r) = h(z, a::r)
             in h(l, [])
            end

fun filter(p, l) =
  let fun h([], r) = rev r
        | h(a::z, r) = if p a then h(z, a::r)
                       else h(z, r)
   in h(l, [])
  end
```

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ML Tutorial (cont'd)

- ***Datatype declaration example :***

```
datatype btree = LEAF
               | NODE of int * btree * btree

fun depth LEAF = 0
  | depth (NODE(_,t1,t2)) = max(depth t1,depth t2)+1

fun insert(LEAF, k) = NODE(k,LEAF,LEAF)
  | insert(NODE(i,t1,t2),k) =
       if k > i then NODE(i,t1,insert(t2,k))
       else if k < i then NODE(i,insert(t1,k),t2)
            else NODE(i,t1,t2)

fun preord(LEAF) = ()
  | preord(NODE(i,t1,t2)) =
          (print i; preord t1; preord t2)
```

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ML Tutorial (cont'd)

- ***use datatype to define a small language (prog. assignment 1) :***

```
type id = string

datatype binop = PLUS | MINUS | TIMES | DIV

datatype stm = SEQ of stm * stm
             | ASSIGN of id * exp
             | PRINT of exp list

and exp = VAR of id
        | CONST of int
        | BINOP of exp * binop * exp
        | ESEQ of stm * exp

(* sample program:          a = 5 + 3; print a *)
val prog =
     SEQ(ASSIGN("a",BINOP(CONST 5,PLUS,CONST 3)),
         PRINT[VAR "a"])
```

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ML Tutorial (cont'd)

- ***Find out the size of program written in the above small language ...***

```
fun sizeS (SEQ(s1,s2)) = sizeS(s1) + sizeS(s2)
  | sizeS (ASSIGN(i,e)) = 2 + sizeE(e)
  | sizeS (PRINT l) = 1 + sizeEL(l)

and sizeE (BINOP(e1,_,e2) = sizeE(e1)+sizeE(e2)+2
  | sizeE (ESEQ(s,e)) = sizeS(s)+sizeE(e)
  | sizeE _ = 1

and sizeEL [] = 0
  | sizeEL (a::r) = (sizeE a)+(sizeEL r)
```

Then `sizeS(prog)` **will return** `8.`

- ***Homework: read Ullman Chapter 1-3 , read Appel Chapter 1, and do Programming Assignment #1 (due January 31, 2017)***

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