CMPT 379
Compilers

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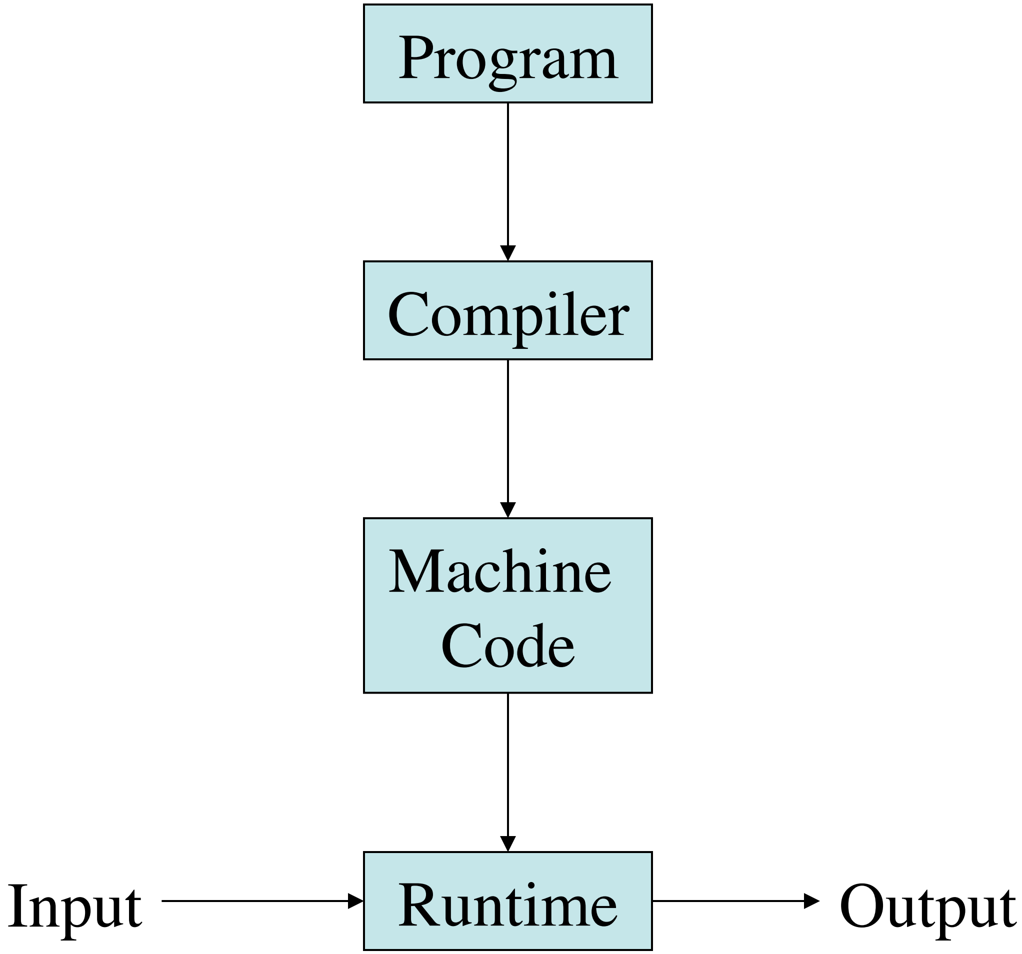
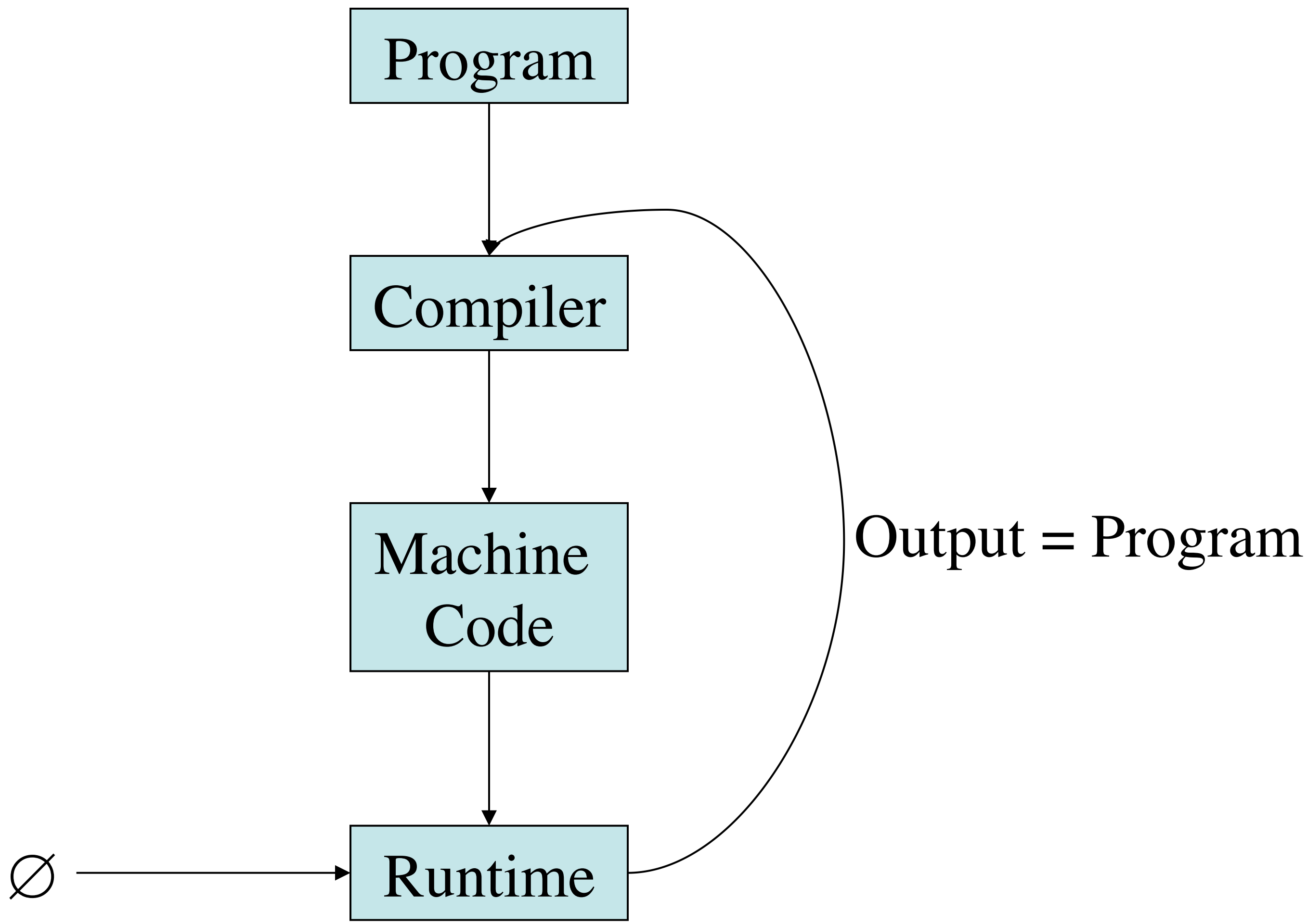
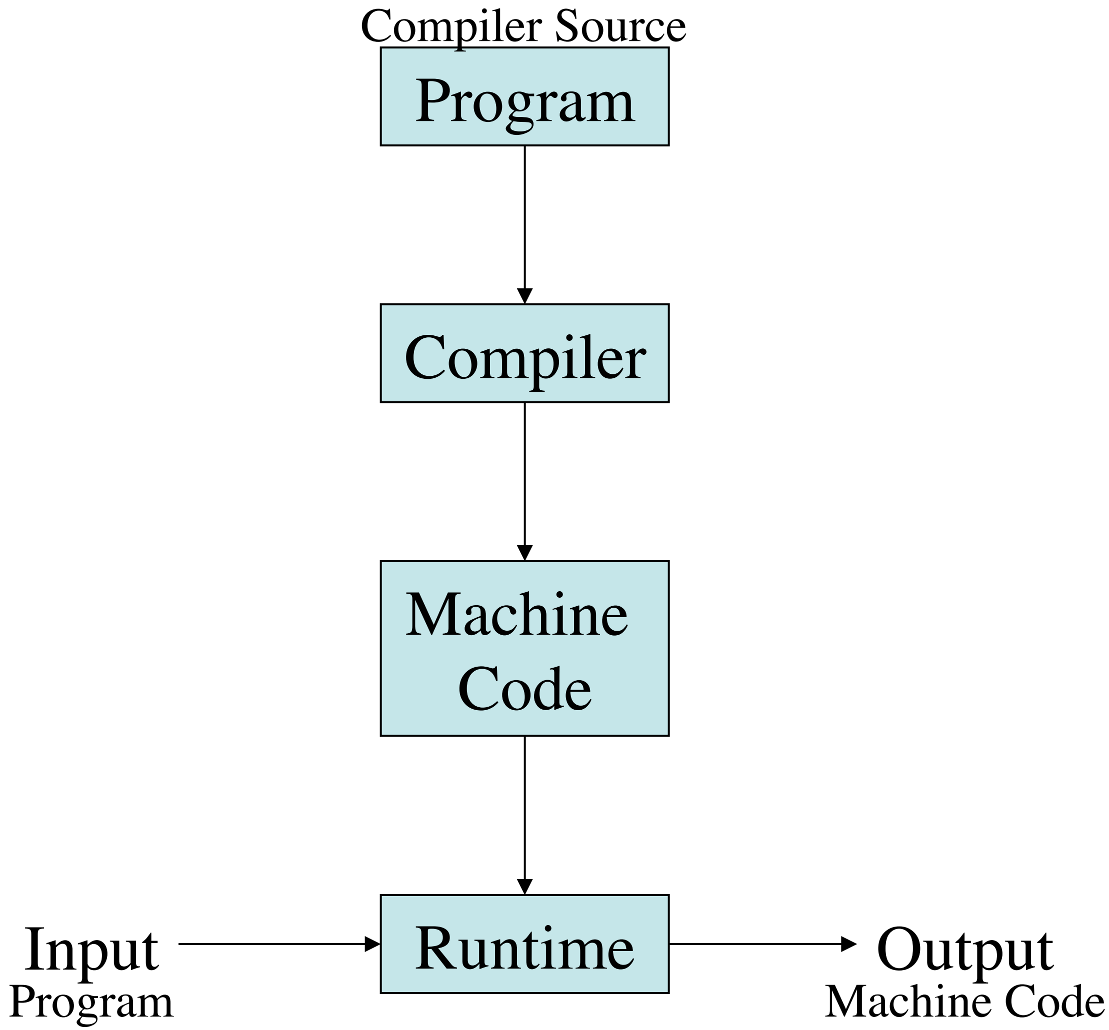
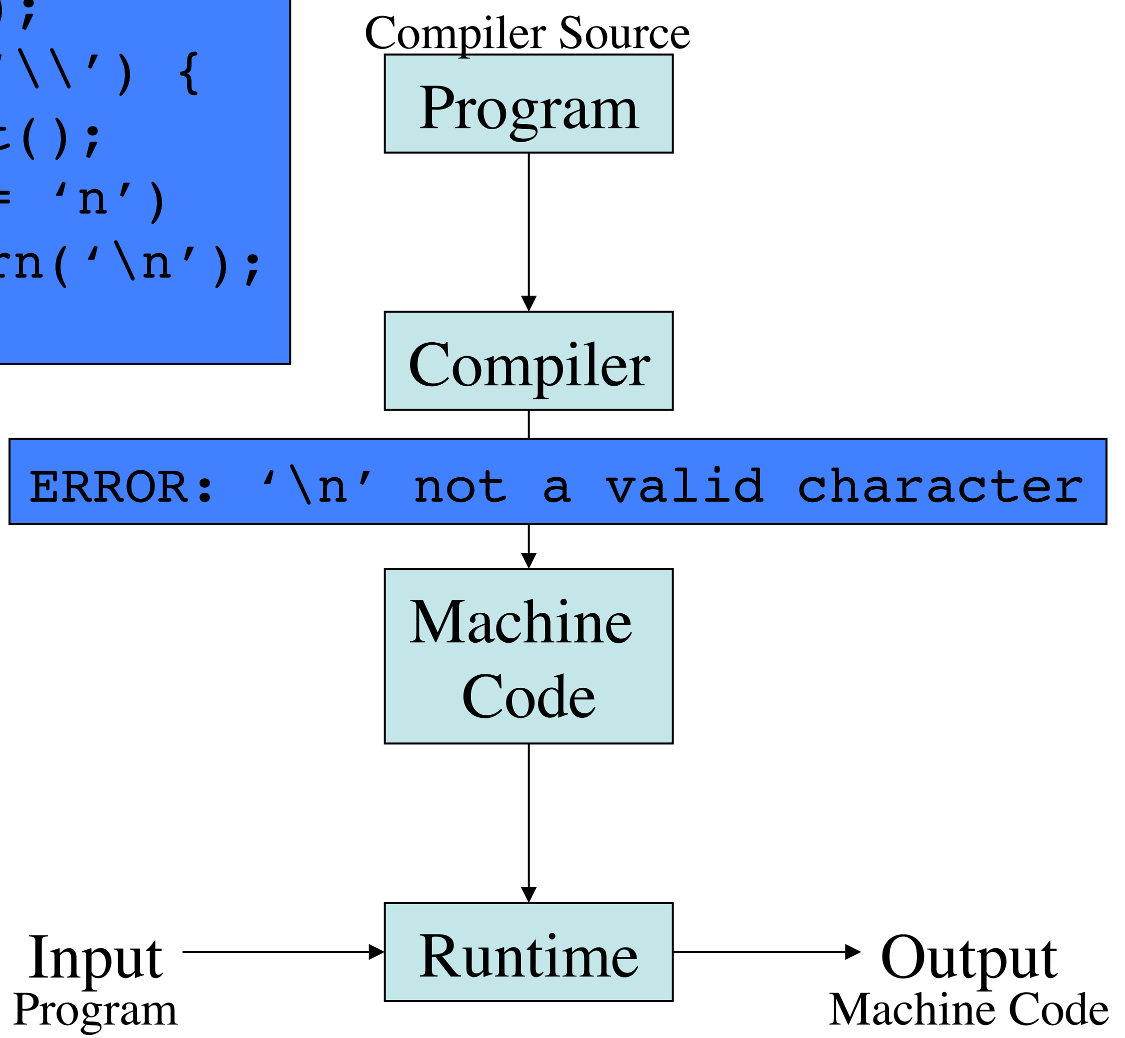

Program
Compiler
Machine Code
Input
Runtime
Output

```
main(){char *c="main(){char *c=%c%s%c;printf(c,34,c,34);}";printf(c,34,c,34);}
```



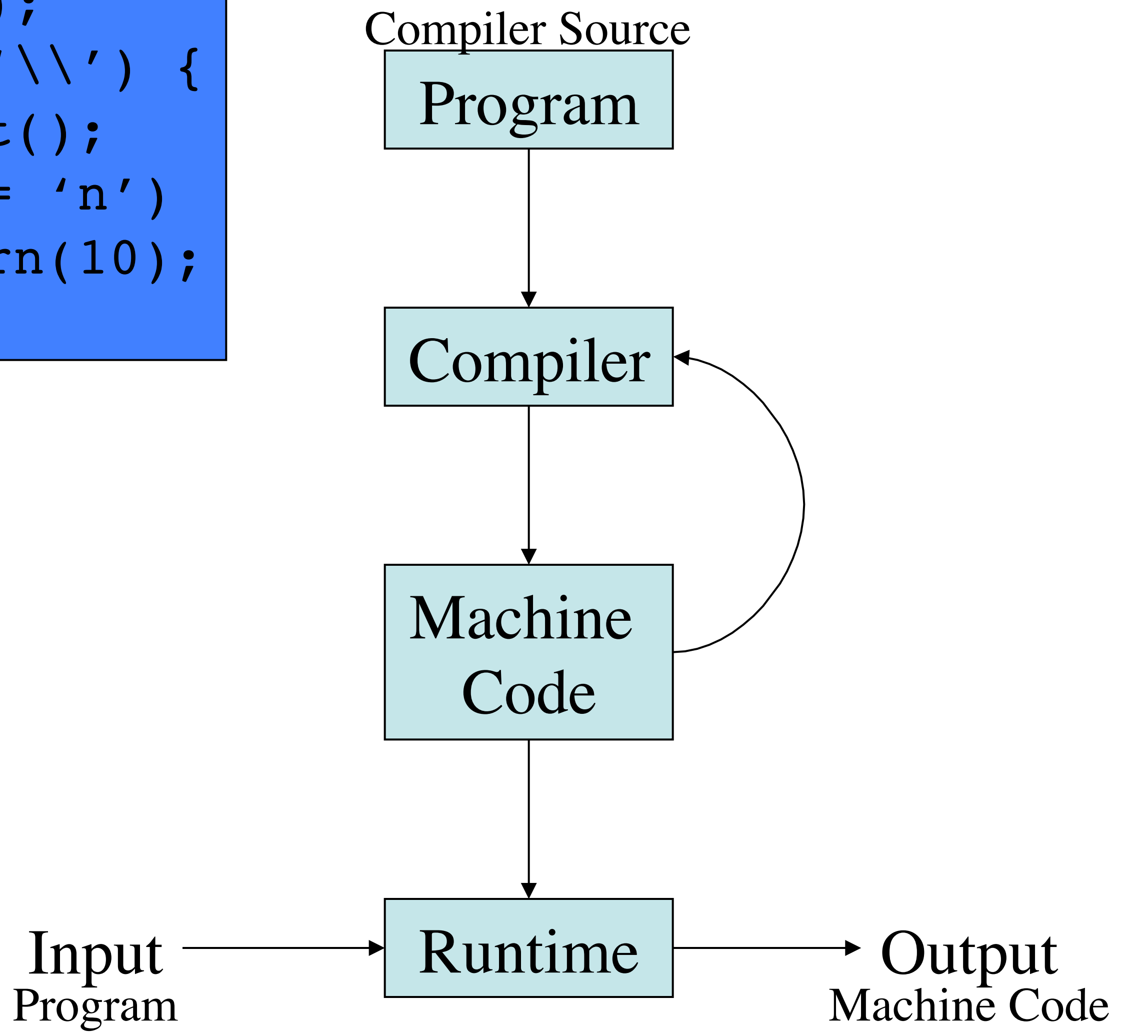

Compiler Source
Program
Compiler
Machine Code
Input
Program
Runtime
Output
Machine Code

```
c = next();
if (c == '\\') {
  c = next();
  if (c == 'n')
     return('\n');
}
```



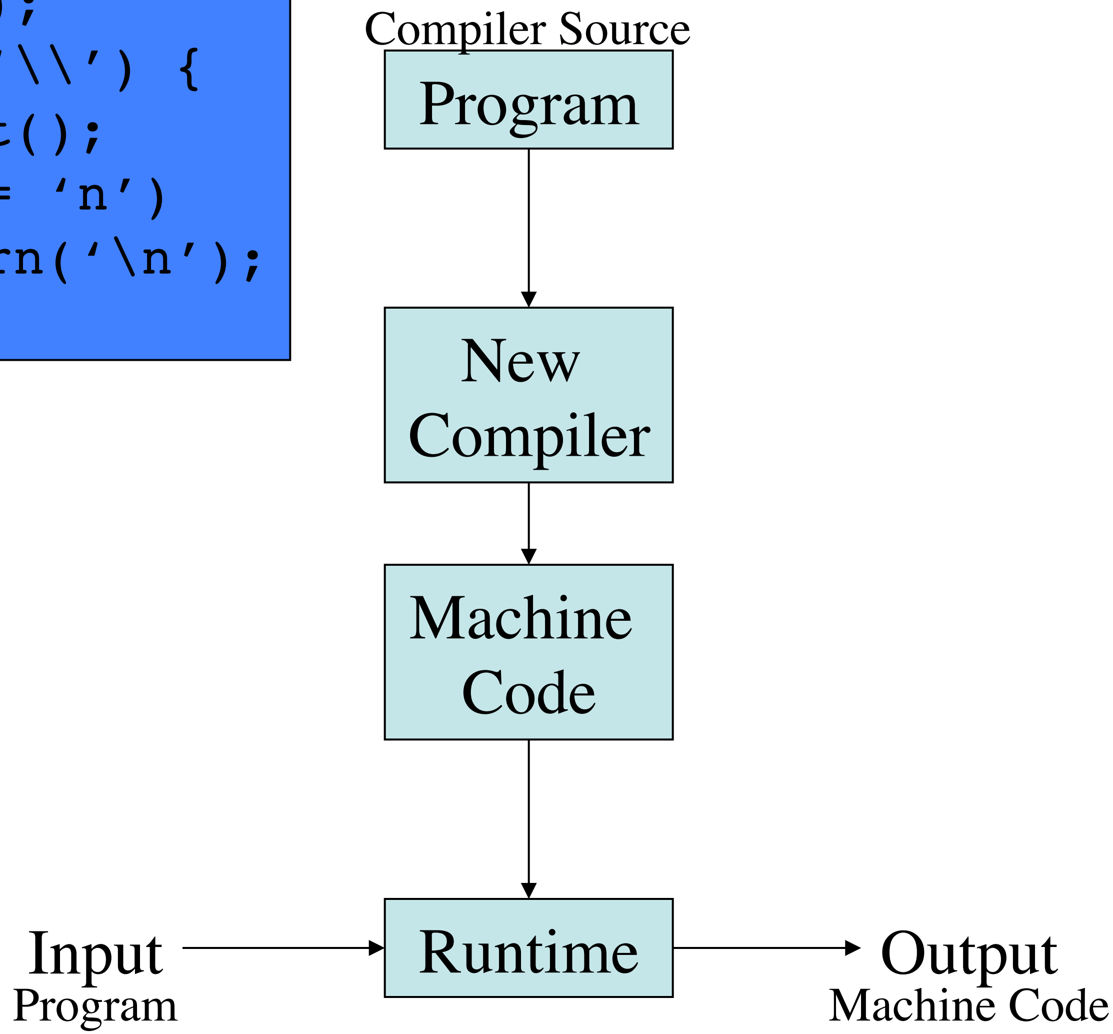

```
printf("hello world\n")
```

```
c = next();
if (c == '\\') {
  c = next();
  if (c == 'n')
     return(10);
}
```



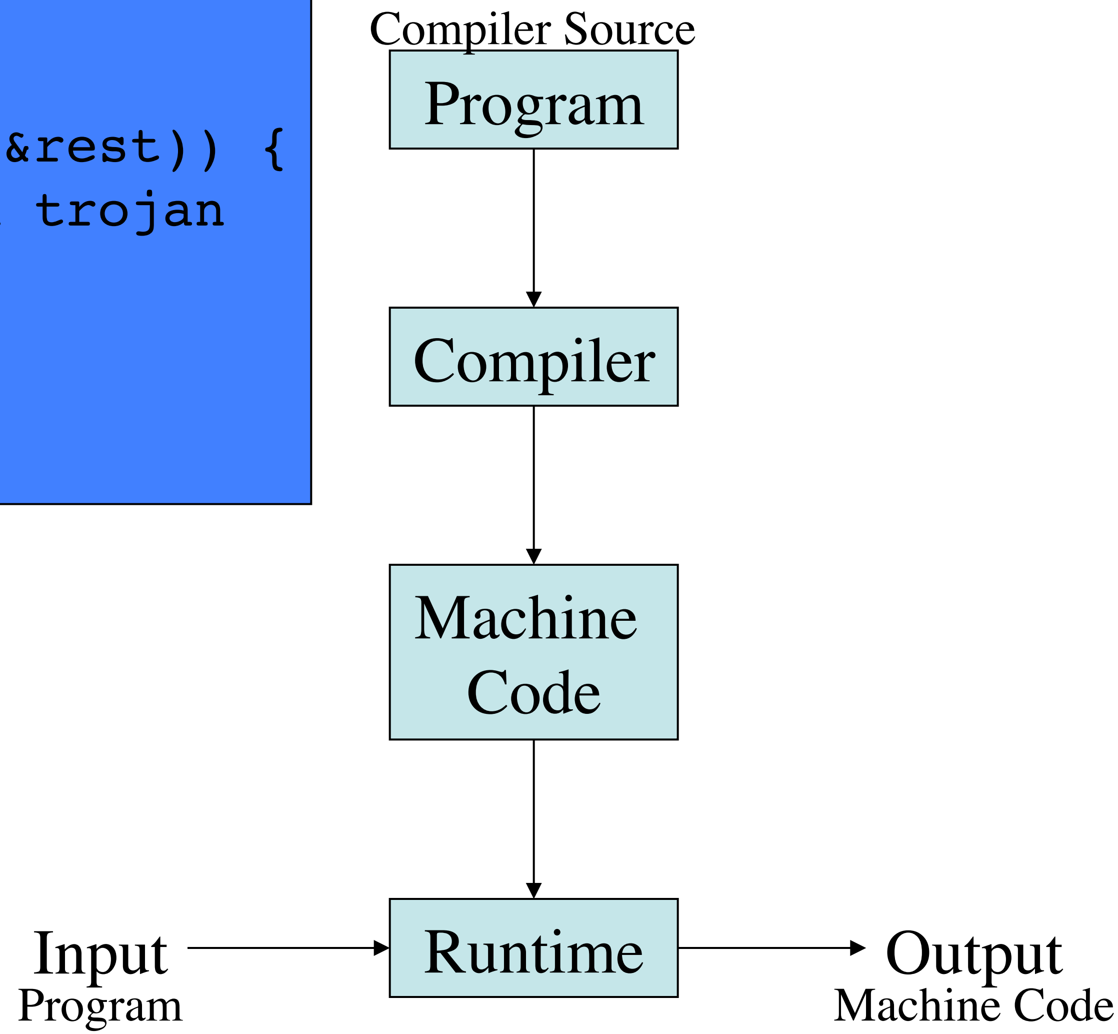

```
printf("hello world\n")
```

```
c = next();
if (c == '\\') {
  c = next();
  if (c == 'n')
     return('\n');
}
```



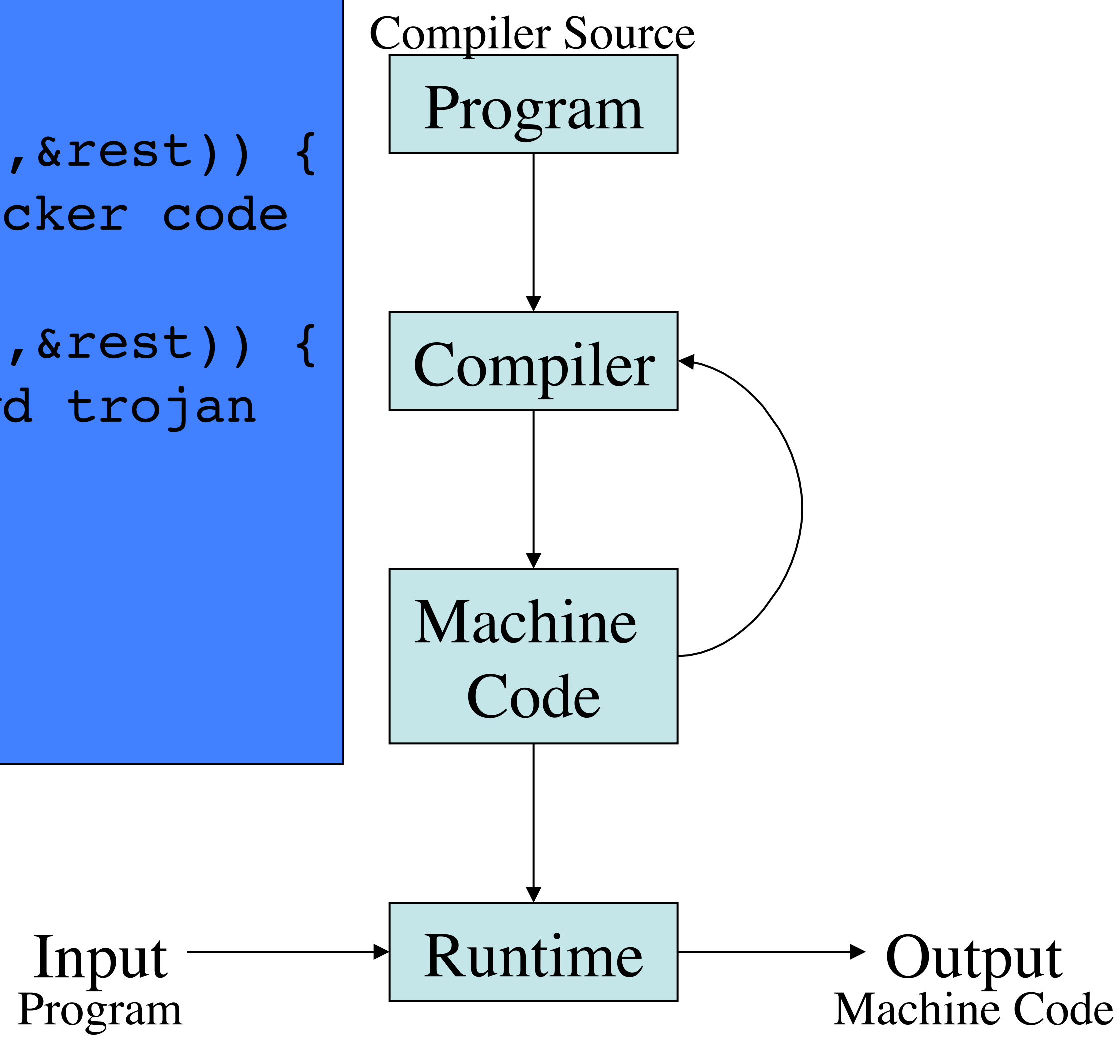

```
printf("hello world\n")
```

```
compile(char *s)
{
  if(match(s,"login(",&rest)) {
    // add root passwd trojan
    compile(rest);
  }
  …
}
```



`Compiler has login crack`

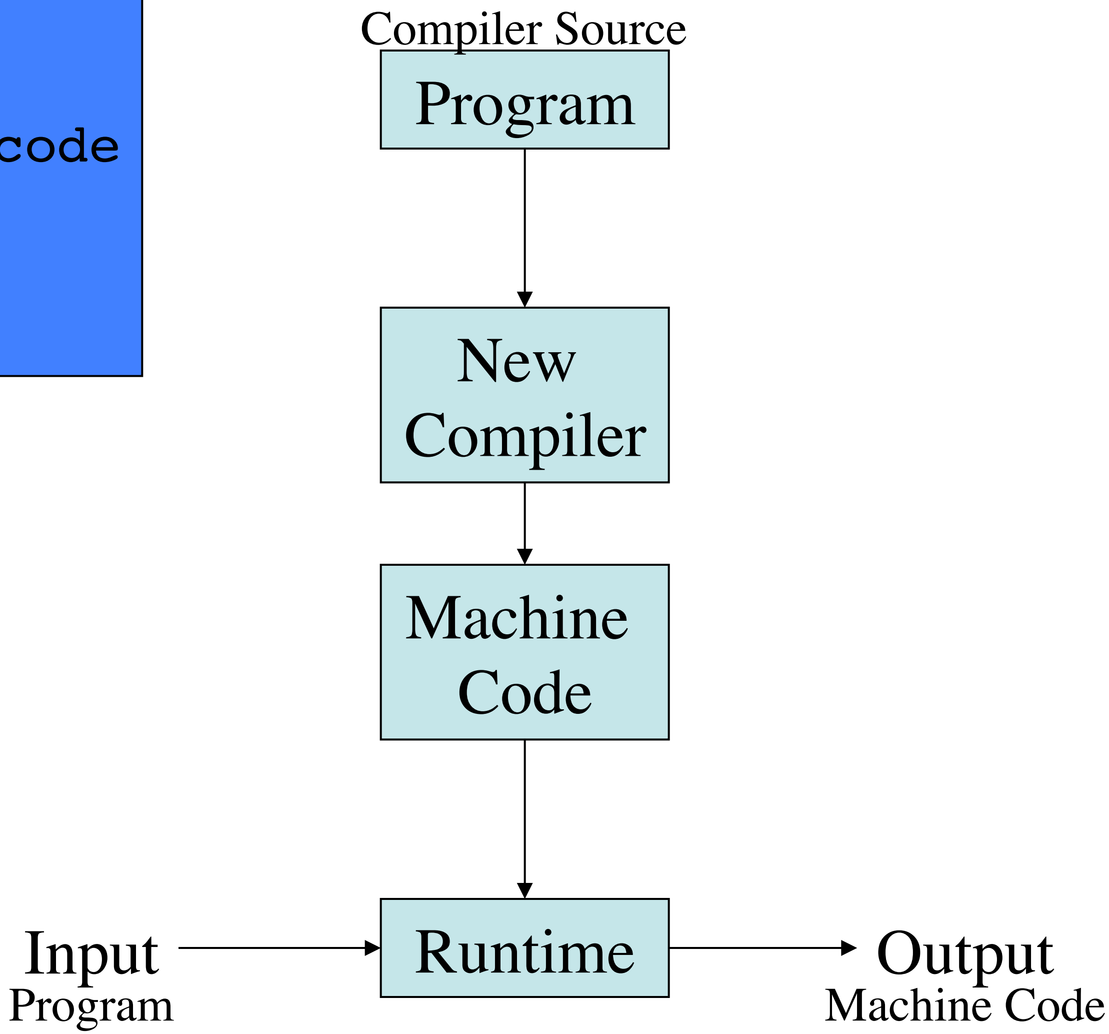
```
compile(char *s)
{
  if(match(s,“compile(”,&rest)) {
    // insert login cracker code
    compile(“
    if(match(s,“login(”,&rest)) {
      // add root passwd trojan
      compile(rest);“);
  }
  compile(rest);
  …
}
```



`Compiler has login crack`

```
compile(char *s)
{
  // standard compiler code
  // no login crack
  …
}
```

Reflections on Trusting Trust,
Ken Thompson.
CACM 27(8), pp. 761-763, 1984.



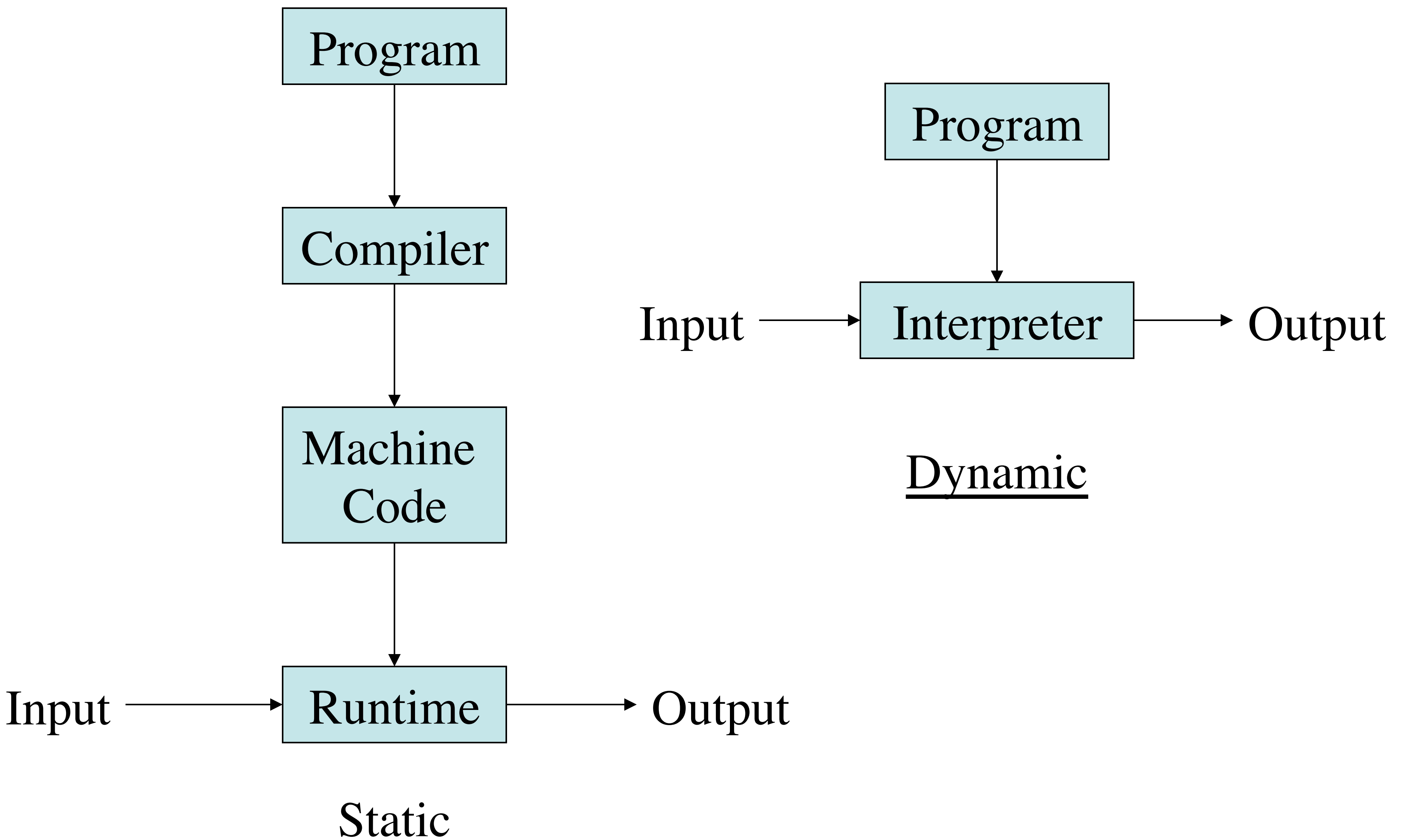
`Compiler inserts login crack`

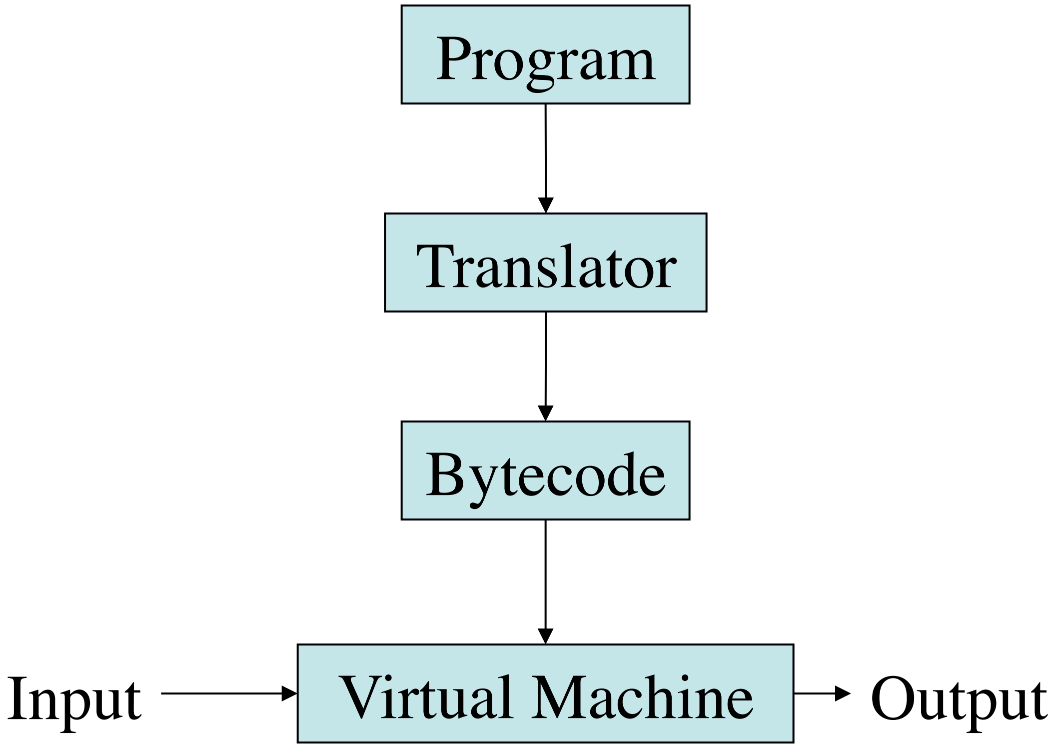
Compilers

- Analysis of the source (front-end)
- Synthesis of the target (back-end)
- The *translation* from user **intention** into intended **meaning**
- The requirements from a Compiler and a Programming Language are:
  - Ease of use (high-level programming)
  - Speed

Cousins of the compiler

- “Smart” editors for structured languages
  - static checkers; pretty printers
- Structured or semi-structured data
  - Trees as data: s-expressions; XML
  - query languages for databases: SQL
- Interpreters (for PLs like lisp or scheme)
  - Scripting languages: perl, python, tcl/tk
  - Special scripting languages for applications
  - “Little” languages: awk, eqn, troff, TeX
- Compiling to Bytecode (virtual machines)


Program
Compiler
Machine Code
Input
Runtime
Output
Static
Program
Input
Interpreter
Output
Dynamic

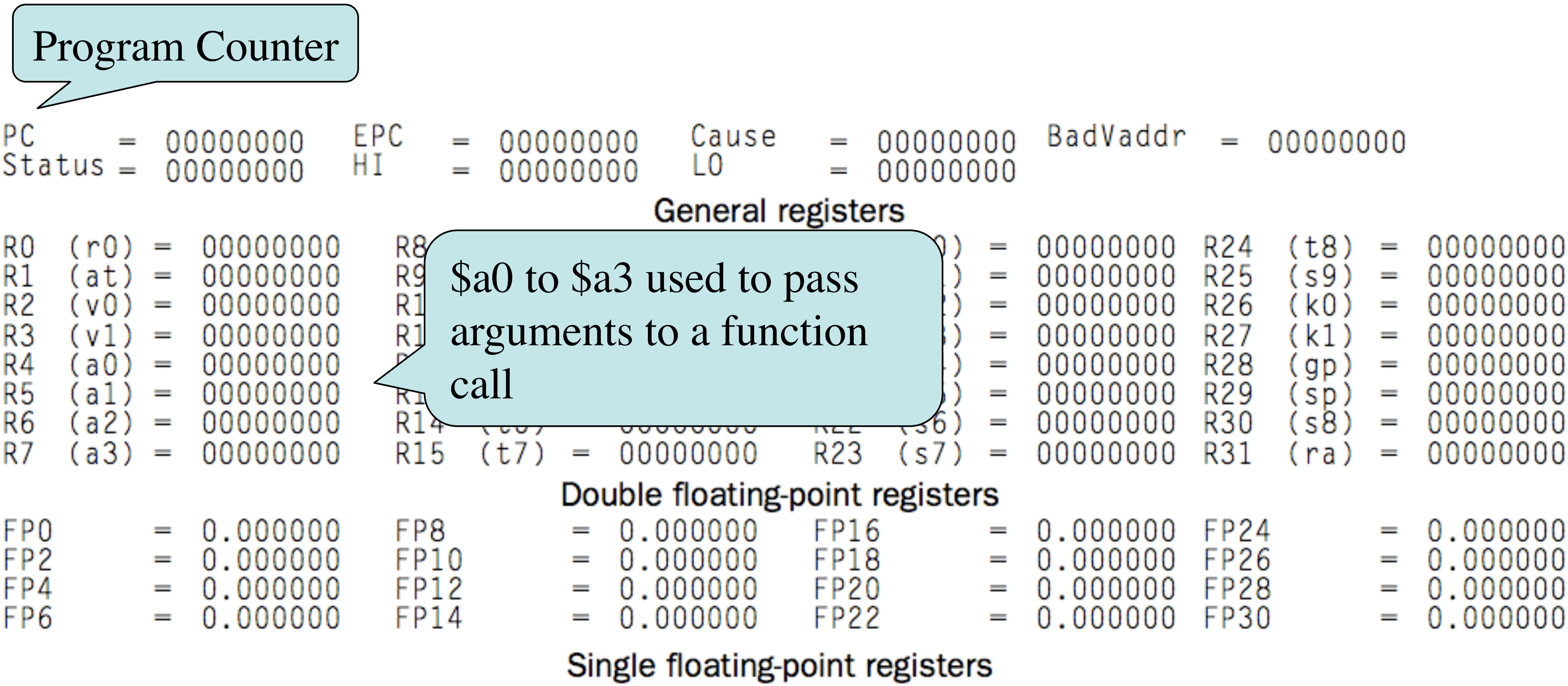


Static/Dynamic

Context for the Compiler

- Preprocessor
- Compiler
- Assembler
- Linker (loader)

MIPS CPU



Program Counter
PC = 00000000 EPC = 00000000 Cause = 00000000 BadVaddr = 00000000
Status = 00000000 HI = 00000000 LO = 00000000
General registers
R0 (r0) = 00000000
R1 (at) = 00000000
R2 (v0) = 00000000
R3 (v1) = 00000000
R4 (a0) = 00000000
R5 (a1) = 00000000
R6 (a2) = 00000000
R7 (a3) = 00000000
R15 (t7) = 00000000
R23 (s7) = 00000000
R24 (t8) = 00000000
R25 (s9) = 00000000
R26 (k0) = 00000000
R27 (k1) = 00000000
R28 (gp) = 00000000
R29 (sp) = 00000000
R30 (s8) = 00000000
R31 (ra) = 00000000
$a0 to $a3 used to pass arguments to a function call
Double floating-point registers
FP0 = 0.000000 FP8 = 0.000000 FP16 = 0.000000 FP24 = 0.000000
FP2 = 0.000000 FP10 = 0.000000 FP18 = 0.000000 FP26 = 0.000000
FP4 = 0.000000 FP12 = 0.000000 FP20 = 0.000000 FP28 = 0.000000
FP6 = 0.000000 FP14 = 0.000000 FP22 = 0.000000 FP30 = 0.000000
Single floating-point registers

MIPS CPU

Text segments

```
[0x00400000]    0x8fa40000   lw $4, 0($29)              ; 89: lw $a0, 0($sp)
[0x00400004]    0x27a50004   addiu $5, $29, 4           ; 90: addiu $a1, $sp, 4
[0x00400008]    0x24a60004   addiu $6, $5, 4            ; 91: addiu $a2, $a1, 4
[0x0040000c]    0x00041080   sll $2, $4, 2              ; 92: sll $v0, $a0, 2
[0x00400010]    0x00c23021   addu $6, $6, $2            ; 93: addu $a2, $a2, $v0
[0x00400014]    0x0c000000   jal 0x00000000 [main]      ; 94: jal main
[0x00400018]    0x3402000a   ori $2, $0, 10             ; 95: li $v0 10
[0x0040001c]    0x0000000c   syscall                    ; 96: syscall
```

Data segments

```
[0x10000000] ... [0x10010000]   0x00000000
[0x10010004]   0x74706563   0x206e6f69   0x636f2000
[0x10010010]   0x72727563   0x61206465   0x6920646e   0x726f6e67
[0x10010020]   0x000a6465   0x495b2020   0x7265746e   0x74707572
[0x10010030]   0x0000205d   0x20200000   0x616e555b   0x6e67696c
[0x10010040]   0x61206465   0x65726464   0x69207373   0x6e69206e
[0x10010050]   0x642f7473   0x20617461   0x63746566   0x00205d68
[0x10010060]   0x555b2020   0x696c616e   0x64656e67   0x64646120
[0x10010070]   0x73736572   0x206e6920   0x726f7473   0x00205d65
```

What we understand

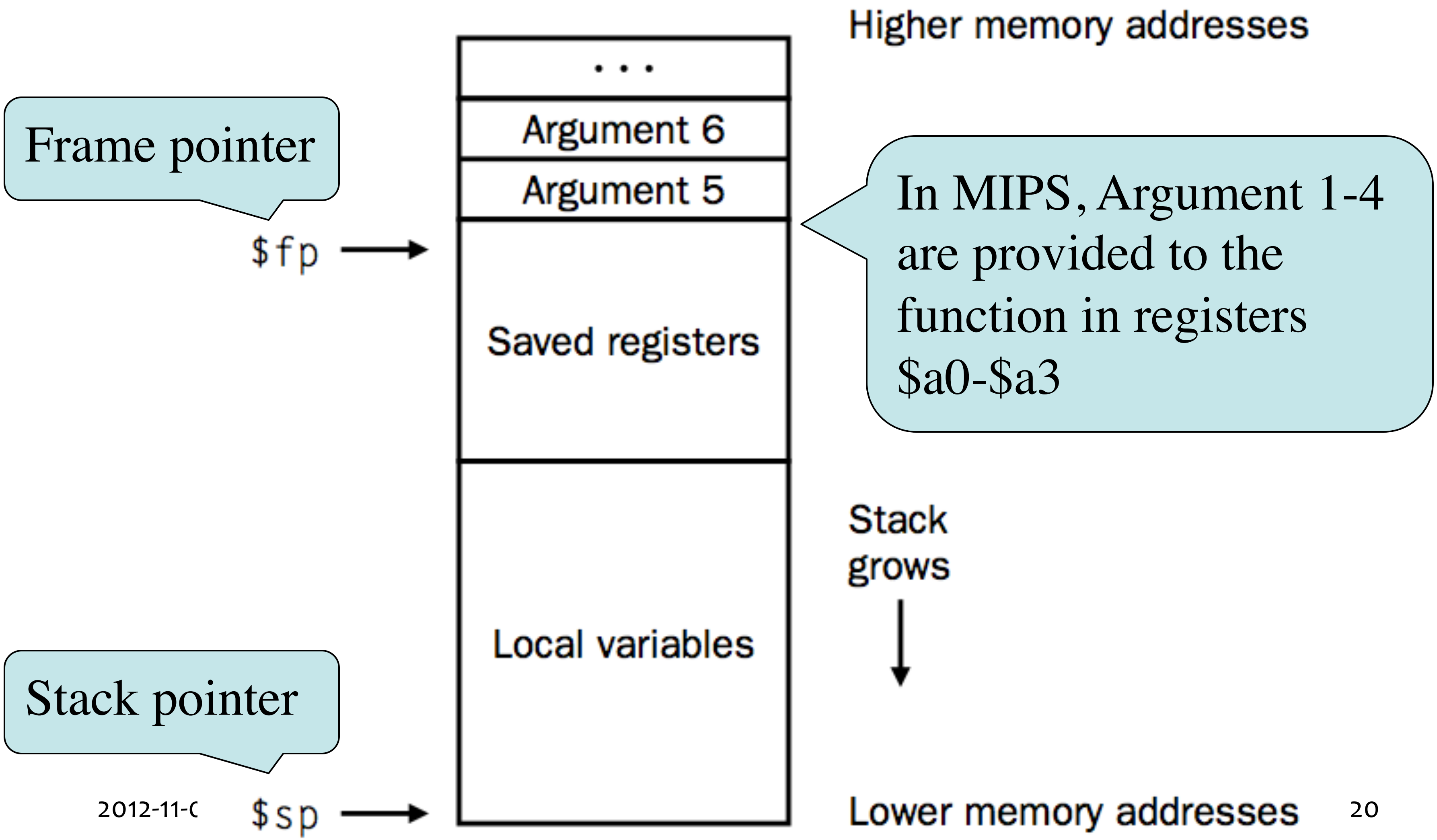
```
#include <stdio.h>

int main (int argc, char *argv[]) {
     int i;
     int sum = 0;
     for (i = 0; i <= 100; i++)
          sum = sum + i * i;
     printf (”Sum from 0..100 = %d\n", sum);
}
```

Assembly language

```
 .text
.align 2
.globl main
main:
  subu $sp, $sp, 32
  sw $ra, 20($sp)
  sd $a0, 32($sp)
  sw $0, 24($sp)
  sw $0, 28($sp)
loop:
  lw $t6, 28($sp)
  mul $t7, $t6, $t6
  lw $t8, 24($sp)
  addu $t9, $t8, $t7
  sw $t9, 24($sp)
  addu $t0, $t6, 1
  sw $t0, 28($sp)
  ble $t0, 100, loop
  la $a0, str
  lw $a1, 24($sp)
  jal printf
  move $v0, $0
  lw $ra, 20($sp)
  addu $sp, $sp, 32
  jr $ra
.data
.align 0
str:
.asciiz "The sum from 0 .. 100 is %d\n"
```

A one-one translation from assembly to machine code

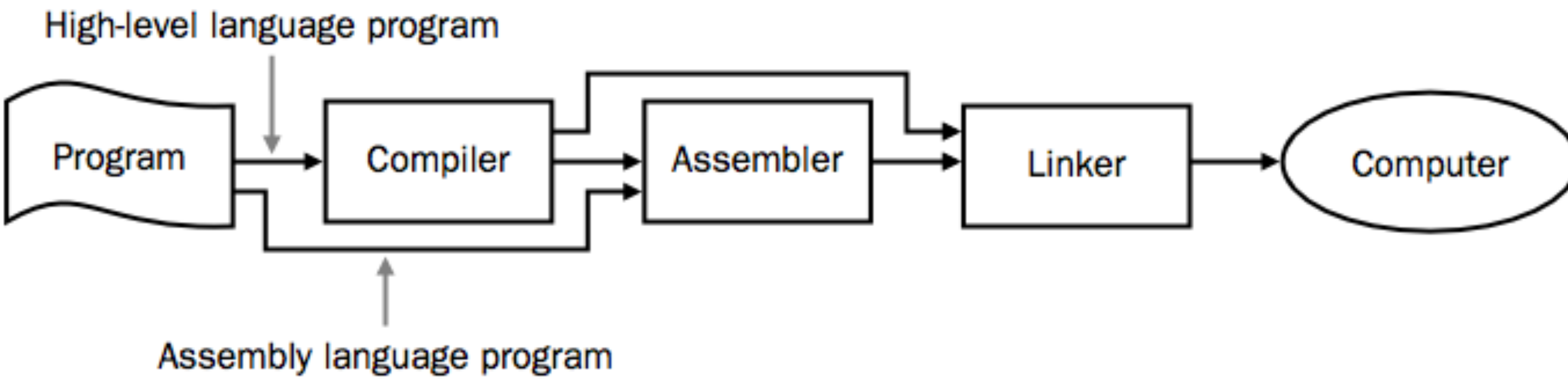
Stack frame


Higher memory addresses
...
Argument 6
Argument 5
Frame pointer
$fp
In MIPS, Argument 1-4 are provided to the function in registers $a0-$a3
Saved registers
Stack grows
Local variables
Stack pointer
$sp
Lower memory addresses

```
00100111101111011111111111100000
10101111101111110000000000010100
10101111101001000000000000100000
10101111101001010000000000100100
10101111101000000000000000011000
10101111101000000000000000011100
10001111101011100000000000011100
10001111101110000000000000011000
00000001110011100000000000011001
00100101110010000000000000000001
00101001000000010000000001100101
10101111101010000000000000011100
00000000000000000111100000010010
00000011000011111100100000100001
00010100001000001111111111110111
10101111101110010000000000011000
00111100000001000001000000000000
10001111101001010000000000011000
00001100000100000000000011101100
00100100100001000000010000110000
10001111101111110000000000010100
00100111101111010000000000100000
00000011111000000000000000001000
00000000000000000001000000100001
```

Conversion into instructions for the Machine

MIPS
machine language
code


High-level language program
Program
Compiler
Assembler
Linker
Computer
Assembly language program

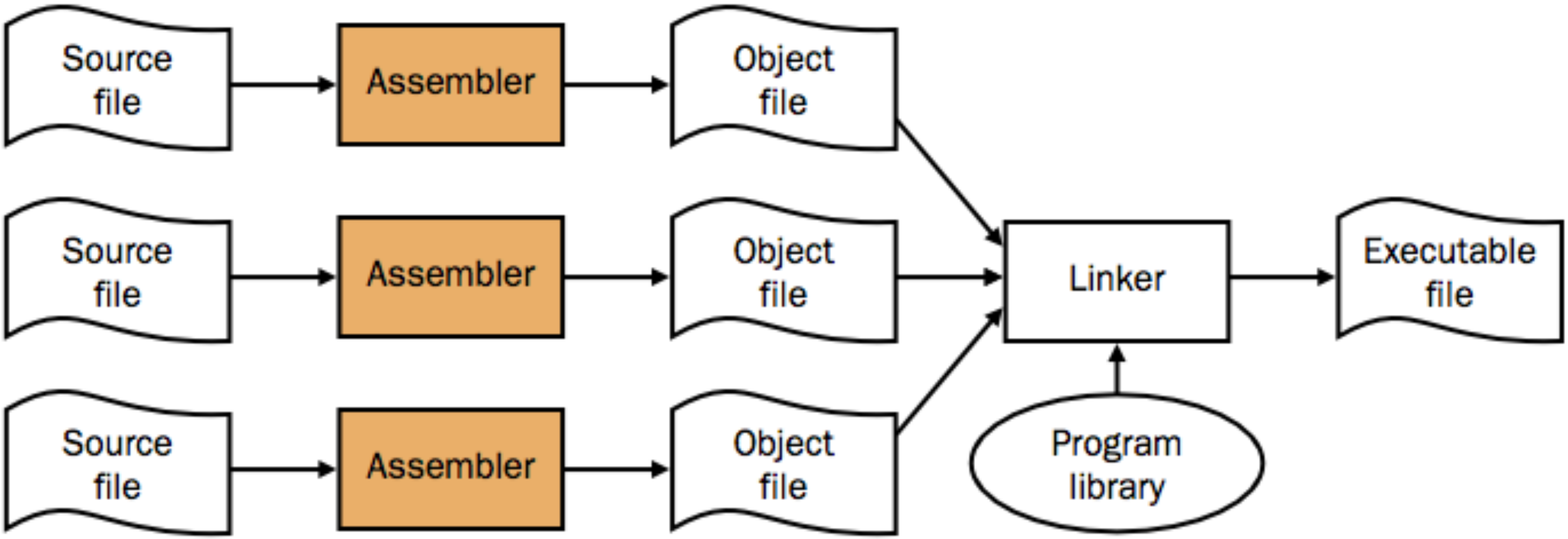
Linker

```
 .data
str:
        .asciiz "the answer = "
.text
main:
        li $v0, 4
        la $a0, str
        syscall

        li $v0, 1
        li $a0, 42
        syscall
```

Local vs. Global labels

2-pass assembler and Linker

The UNIX toolchain (`as`, `ar`, `ranlib`, `ld`, …)



Historical Background

- 1940s-1950s: Machine language/Assembly language
- 1957: First FORTRAN compiler
  - 18 person years of effort
- Other early languages: COBOL, LISP
- Today's techniques were created in response to the difficulties of implementing early compilers

Programming Language Design

- Ease of use (difficult to define precisely)
- Simplicity
- Visualize the dynamic process of the programs runtime by examining the static program code
- Code reuse: polymorphic functions, objects
- Checking for correctness: strong vs. weak typing, side-effects, formal models

Programming Language Design

- The less typing the better: syntactic "sugar"
- Automatic memory management
- Community acceptance: extensions and libraries
- Speed (closely linked to the compiler tools)
- Defining tokens and the syntax
- Defining the "semantics" (typing, polymorphism, coercion, etc.)

Programming Language Design

- Environments and states; scoping rules
  - Environment: names to memory locations (l-values)
  - State: locations to values (r-values)
- Core language vs. the standard library
- Hooks for code optimization (iterative idioms vs. pure functional languages)

Building a compiler

- Programming languages have a lot in common
- Do not write a compiler for each language
- Create a general mathematical model for all languages: implement this model
- Each language compiler is built using this general model (so-called *compiler compilers*)
  - yacc = yet another compiler compiler
- Code optimization ideas can also be shared across languages

Building a compiler

- The cost of compiling and executing should be managed
- No program that violates the definition of the language should escape
- No program that is valid should be rejected

Building a compiler

- Requirements for building a compiler:
  - Symbol-table management
  - Error detection and reporting
- Stages of a compiler:
  - Analysis (front-end)
  - Synthesis (back-end)

Stages of a Compiler

- Analysis (Front-end)
  - Lexical analysis
  - Syntax analysis (parsing)
  - Semantic analysis (type-checking)
- Synthesis (Back-end)
  - Intermediate code generation
  - Code optimization
  - Code generation

Lexical Analysis

- Also called *scanning*, take input program *string* and convert into tokens
- Example:

```
double f = sqrt(-1);
```

```
T_DOUBLE      ("double")
T_IDENT       ("f")
T_OP          ("=")
T_IDENT       ("sqrt")
T_LPAREN      ("(")
T_OP          ("-")
T_INTCONSTANT ("1")
T_RPAREN      (")")
T_SEP         (";")
```

Syntax Analysis

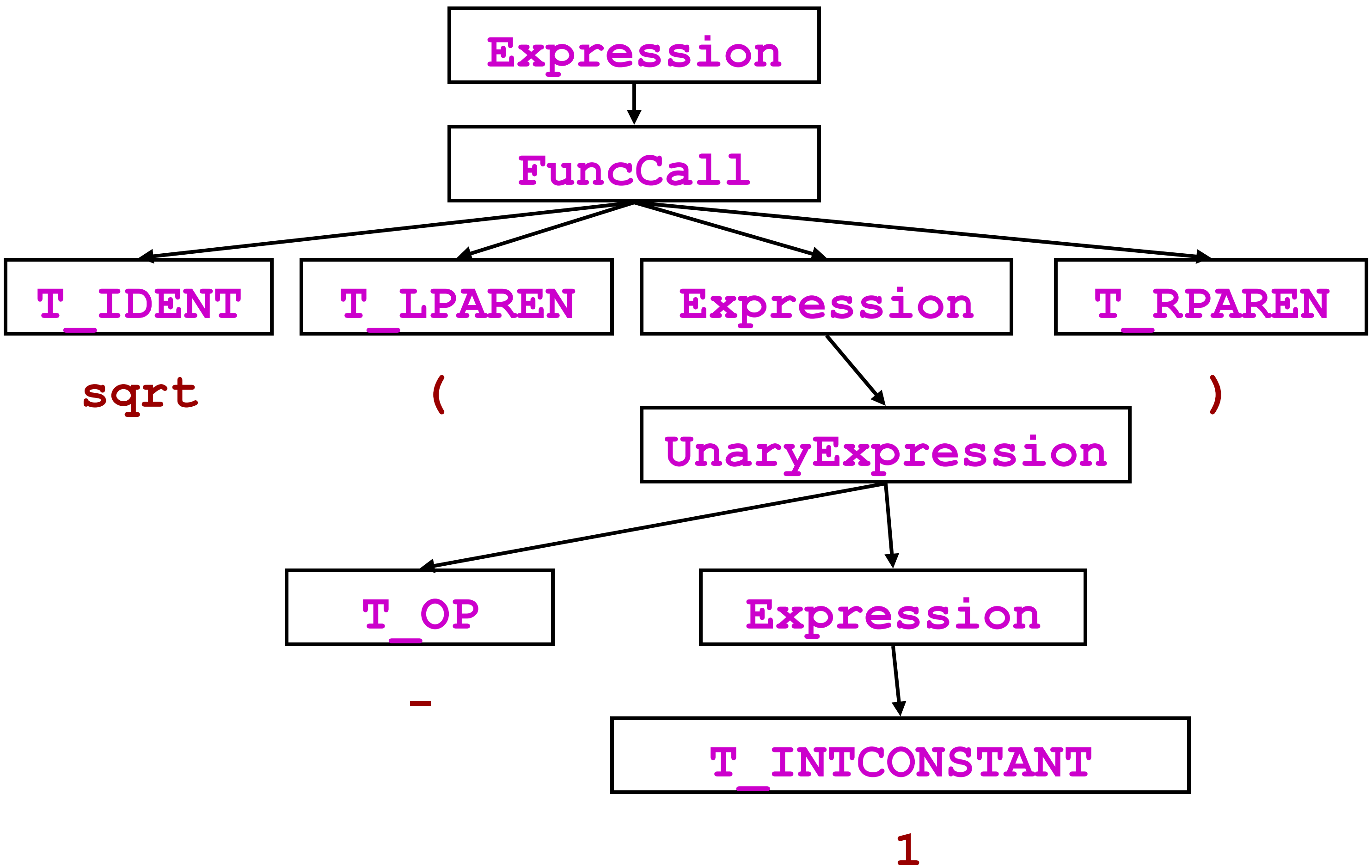
- Also called *parsing*
- Describe the set of strings that are programs using a grammar
- Pick the simplest grammar formalism possible (but not too simple)
  - Finite-state machines (Regular grammars)
  - Deterministic Context-free grammars
  - Context-free grammars
- Structural validation
- Creates parse tree or derivation

Derivation of `sqrt(-1)`

```
Expression -> UnaryExpression
Expression -> FuncCall
Expression -> T_INTCONSTANT
UnaryExpression -> T_OP Expression
FuncCall  -> T_IDENT T_LPAREN Expression T_RPAREN
```

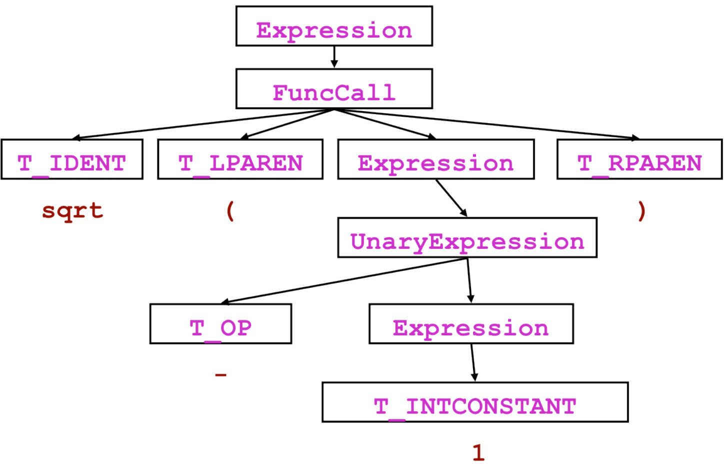
```
Expression
   -> FuncCall
   -> T_IDENT T_LPAREN Expression T_RPAREN
   -> T_IDENT T_LPAREN UnaryExpression T_RPAREN
   -> T_IDENT T_LPAREN T_OP Expression T_RPAREN
   -> T_IDENT T_LPAREN T_OP T_INTCONSTANT T_RPAREN
```

Parse Trees



Expression
FuncCall
T_IDENT
T_LPAREN
Expression
T_RPAREN
sqrt
(
)
UnaryExpression
T_OP
Expression
-
T_INTCONSTANT
1

Abstract Syntax Tree




```
[Expr(
      value=Call(
            func=Attribute(
                  value=Name(
                        id='math',
                        ctx=Load()
                  ),
                  attr='sqrt',
                  ctx=Load()
            ),
            args=[Num(n=-1)],
            keywords=[],
            starargs=None,
            kwargs=None
      )
  )
]
```

Semantic analysis

- "does it make sense"? Checking semantic rules,
  - Is there a `main` function?
  - Is variable declared?
  - Are operand types compatible? (coercion)
  - Do function arguments match function declarations?
- Type checking: *operational* or *denotational* semantics
- Static vs. run-time semantic checks
  - Array bounds, return values do not match definition

Intermediate Code Generation

- Three-address code (TAC)

```
j = 2 * i + 1;
if (j >= n)
   j = 2 * i + 3;
return a[j];
```

```
      _t1 = 2 * i
      _t2 = _t1 + 1
      j = _t2
      _t3 = j < n
      if _t3 goto L0
      _t4 = 2 * i
      _t5 = _t4 + 3
      j = _t5
L0:   _t6 = a[j]
      return _t6
```

Code Optimization

- Example

```
        _t1 = 2 * i
        _t2 = _t1 + 1
        j = _t2
        _t3 = j < n
        if _t3 goto L0
        _t4 = 2 * i
        _t5 = _t4 + 3
        j = _t5
L0:     _t6 = a[j]
        return _t6
```

```
        _t1 = 2 * i

        j = _t1 + 1
        _t3 = j < n
        if _t3 goto L0

        j = _t1 + 3

L0:     _t6 = a[j]
        return _t6
```

Object code generation

- Example: *a* in `$a0`, *i* in `$a1`, *n* in `$a2`

```
_t1 = 2 * i

j = _t1 + 1
_t3 = j < n
if _t3 goto L0

j = _t1 + 3
```

```
mulo $t1, $a0, 2

add $s0, $t1, 1
seq $t2, $s0, $a2
beq $t2, 1, L0

add $s0, $t1, 3
```

Bootstrapping a Compiler

- Machine code at the beginning
- Make a simple subset of the language, write a compiler for it, and then use that subset for the rest of the language definition
- Bootstrap from a simpler language
  - C++ (“C with classes”)
- Interpreters
- Cross compilation

Modern challenges

- Instruction Parallelism
  - Out of order execution; branch prediction
- Parallel algorithms:
  - Grid computing,
  - multi-core computers
- Memory hierarchy: register, cache, memory
- Binary translation, e.g. x86 to VLIW
- New computer architectures, e.g. streaming algorithms
- Hardware synthesis / Compiled simulations

Wrap Up

- Analysis/Synthesis
  - Translation from string to executable
- Divide and conquer
  - Build one component at a time
  - Theoretical analysis will ensure we keep things **simple** and **correct**
  - Create a complex piece of software