Programming Languages and Translators

Stephen A. Edwards

Columbia University

Fall 2016

Pieter Bruegel, *The Tower of Babel*, 1563
Facebook on 4115

Aho vs. Edwards for PLT?
Does anyone have strong opinions about either professor?
Thanks!

Stephen A. Edwards Definitely take it from Aho
November 17 at 1:54pm · Like · 150

Sadly, Aho has retired from teaching 4115.
Prof. Stephen A. Edwards
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http://www.cs.columbia.edu/~sedwards/
462 Computer Science Building
Email me for appointments
Edwards is the snarkiest, most sarcastic, immature professor you will meet in the CS department. He tells some really great nerdy jokes and his Facebook wall is hilarious since he belittles all his students publicly on it, but I don't recommend taking his class. Don't ever email him with an excuse or stupid question since he will publicly shame you (name removed though) on Facebook.
Objectives

Theory

- Principles of modern programming languages
- Fundamentals of compilers: parsing, type checking, code generation
- Models of computation

Practice: Semester-long Team Project

- Design and implement your own language and compiler
- Code it in the OCaml functional language
- Manage the project and your teammates; communicate
Quasi-required Text

Alfred V. Aho, Monica S. Lam, Ravi Sethi, and Jeffrey D. Ullman.

*Compilers: Principles, Techniques, and Tools.*


Bug Al about all bugs.

You can get away with the first edition.
Schedule

Lectures: Mondays and Wednesdays, 4:10 – 5:25
207 Mathematics
September 7 – December 12

Exam 1: October 17
Exam 2: December 12

Presentations: December 20
Final Team project reports: December 20

You can present before December 20 if you want to travel early. All team members must present.
Assignments and Grading

40% Team Programming Project
20% Exam 1
30% Exam 2
10% Three individual homework assignments

Team project is most important, but most students do well on it. Grades for tests often vary more.
Prerequisites

COMS W3157 Advanced Programming

- How to work on a large software system in a team
- Makefiles, version control, test suites
- Testing will be as important as coding

COMS W3261 Computer Science Theory

- Regular languages and expressions
- Context-free grammars
- Finite automata (NFAs and DFAs)
Collaboration

Collaborate with your team on the project.

Do your homework by yourself.


Don’t be a cheater (e.g., copy from each other):
    If you’re dumb enough to cheat,
        I’m smart enough to catch you.

Nearly every term I’ve caught cheaters and sent them to the dean. Please try to break my streak.
The Team Project
The Team Project

Design and implement your own little language.

Six deliverables:

1. A proposal describing your language
2. A language reference manual defining it formally
3. An intermediate milestone: compiling "Hello World."
4. A compiler for it, running sample programs
5. A final project report
6. A final project presentation
Teams

Immediately start forming four-person teams
Each team will develop its own language
Assign each team member a specific role

<table>
<thead>
<tr>
<th>Role</th>
<th>Responsibilities</th>
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<tbody>
<tr>
<td>Manager</td>
<td>Timely completion of deliverables</td>
</tr>
<tr>
<td>Language Guru</td>
<td>Language design</td>
</tr>
<tr>
<td>System Architect</td>
<td>Compiler architecture, development environment</td>
</tr>
<tr>
<td>Tester</td>
<td>Test plan, test suites</td>
</tr>
</tbody>
</table>
QA ENGINEER WALKS INTO A BAR
ORDERS A BEER
ORDERS NULL BEERS
ORDERS 1.33 BEERS
ORDERS A LIZARD
ORDERS -1 BEERS
ORDERS 😊 BEERS
START EARLY, and really be selective in picking your team. A bad team will ruin the semester for you.
EVERY GROUP PROJECT

DOES 99% OF THE WORK

SAYS HE'S GOING TO HELP BUT HE'S NOT

HAS NO IDEA WHAT'S GOING ON THE WHOLE TIME

DISAPPEARS AT THE VERY BEGINNING AND DOESN'T SHOW UP AGAIN TIL THE VERY END

IN SCHOOL YOU HAVE EVER DONE
When I die I want my group project members to lower me into my grave so they can let me down one last time.
How Do You Work In a Team?

If I knew, I’d use the knowledge to take over the world

- Address problems sooner rather than later
  If you think your teammate’s a flake, you’re right

- Complain to me or your TA as early as possible
  Alerting me a day before the project is due isn’t helpful

- Not every member of a team will get the same grade
  Remind your slacking teammates of this early and often

- I have forcibly split and dissolved teams
  If someone is really underperforming, dump his ass
What Google Learned From Its Quest to Build the Perfect Team

Things that did not matter

× Members’ intelligence
× Members’ experience
× Mix of personality types
× Whether the members were close friends
× Strong organization
× Gender balance

http://mobile.nytimes.com/2016/02/28/magazine/
what-google-learned-from-its-quest-to-build-the-perfect-team.html

https://hunterwalk.com/2016/09/03/
google-finds-that-successful-teams-are-about-norms-not-just-smarts/
What Google Learned From Its Quest to Build the Perfect Team

Things that *did* matter

Team “norms.” Unwritten rules of team interaction.

- That every team member spoke in the same proportion
- That team members had “social sensitivity”
  Empathy for fellow team members: the ability to read others’ feelings through void, expressions, etc.
First Three Tasks

1. Decide who you will work with
   You’ll be stuck with them for the term; choose wisely.

2. Assign a role to each member
   Languages come out better from dictatorships, not democracies.

3. Select a weekly meeting time
   Harder than you might think.
Describe the language that you plan to implement.

Explain what sorts of programs are meant to be written in your language

Explain the parts of your language and what they do

Include the source code for an interesting program in your language

2–4 pages
A careful definition of the syntax and semantics of your language.

Follow the style of the C language reference manual (Appendix A of Kernighan and Ritchie, *The C Programming Language*; see the class website).
## Final Report Sections

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<td>Conclusions</td>
<td>Team</td>
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<tr>
<td>Full Code Listing</td>
<td>Team</td>
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## Project Due Dates

<table>
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<tr>
<th>Project</th>
<th>Due Date</th>
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<tr>
<td>Proposal</td>
<td>September 28 soon</td>
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<tr>
<td>Language Reference Manual</td>
<td>October 26</td>
</tr>
<tr>
<td>Hello World Demo</td>
<td>November 21</td>
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<tr>
<td>Final Report</td>
<td>December 20</td>
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Design a language?

A domain-specific language: awk or PHP, not Java or C++.

Examples from earlier terms:
Matlab-like array manipulation language
Geometric figure drawing language
Music manipulation language
Mathematical function manipulator
Simple scripting language (à lá Tcl)
Three Common Mistakes to Avoid

Configuration File Syndrome

- Must be able to express *algorithms*, not just data
- E.g., a program like “a bird and a turtle and a pond and grass and a rock,” is just data, not an algorithm

Standard Library Syndrome

- Good languages express lots by a combining few things
- Write a standard library in your language
- Aim for Legos, not Microsoft Word

Java-to-Java Translator Syndrome

- A compiler mostly adds implementation details to code
- Your compiler’s output should not look like its input
- Try your best not to re-invent Java
What I’m Looking For

Your language must be able to express different algorithms

- Avoid Configuration File Syndrome. Most languages should be able to express, e.g., the GCD algorithm.

Your language should consist of pieces that can mix freely

- Avoid Standard Library Syndrome. For anything you provide in the language, ask yourself whether you can express it using other primitives in your language.

Your compiler must lower the level of abstraction

- Don’t write a Java-to-Java translator. Make sure your compiler adds details to the output such as registers, evaluation order of expressions, stack management instructions, etc.
What’s in a Language?
Components of a language: Syntax

How characters combine to form words, sentences, paragraphs.

*The quick brown fox jumps over the lazy dog.*

is syntactically correct English, but isn’t a Java program.

```java
class Foo {
    public int j;
    public int foo(int k) { return j + k; }
}
```

is syntactically correct Java, but isn’t C.
Specifying Syntax

Usually done with a context-free grammar.

Typical syntax for algebraic expressions:

```
expr  →  expr + expr
   |  expr − expr
   |  expr * expr
   |  expr / expr
   |  digit
   |  (expr)
```
Components of a language: Semantics
What a well-formed program “means.”

The semantics of C says this computes the $n$th Fibonacci number.

```c
int fib(int n)
{
    int a = 0, b = 1;
    int i;
    for (i = 1 ; i < n ; i++) {
        int c = a + b;
        a = b;
        b = c;
    }
    return b;
}
```

‘When I use a word,’ Humpty Dumpty said in rather a scornful tone, ‘it means just what I choose it to mean—neither more nor less.’

Semantics

Something may be syntactically correct but semantically nonsensical

*The rock jumped through the hairy planet.*

Or ambiguous

*The chickens are ready to eat.*
Semantics

Nonsensical in Java:

```java
class Foo {
    int bar(int x) { return Foo; }
}
```

Ambiguous in Java:

```java
class Bar {
    public float foo() { return 0; }
    public int foo() { return 0; }
}
```
Great Moments in Evolution
Assembly Language

Before: numbers
55
89E5
8B4508
8B550C
39D0
740D
39D0
7E08
29D0
39D0
75F6
C9
C3
29C2
EBF6

After: Symbols

gcd: pushl %ebp
    movl %esp, %ebp
    movl 8(%ebp), %eax
    movl 12(%ebp), %edx
    cmpl %edx, %eax
    je .L9
.L7: cmpl %edx, %eax
    jle .L5
    subl %edx, %eax
.L2: cmpl %edx, %eax
    jne .L7
.L9: leave
    ret
.L5: subl %eax, %edx
    jmp .L2
**Before**

```
gcd: pushl %ebp
    movl %esp, %ebp
    movl 8(%ebp), %eax
    movl 12(%ebp), %edx
    cmpl %edx, %eax
    je .L9
.L7: cmpl %edx, %eax
    jle .L5
    subl %edx, %eax
.L2: cmpl %edx, %eax
    jle .L5
    subl %edx, %eax
.L9: leave
    ret
.L5: subl %eax, %edx
    jmp .L2
```

**After: Expressions, control-flow**

```
10   if (a .EQ. b) goto 20
10     if (a .LT. b) then
10       a = a - b
10     else
10       b = b - a
10     endif
10     goto 10
20   end
```
program ninetyninebottles
integer bottles
bottles = 99
  1 format (I2, A)
  2 format (A)
  3 format (I2, A, /)
  4 format (A, /)
 10 write (*,1) bottles, ' bottles of beer on the wall,'
write (*,1) bottles, ' bottles of beer.'
write (*,2) 'Take one down, pass it around...'
  if (bottles - 1 .gt. 1) then
     write (*,3) bottles - 1, ' bottles of beer on the wall.'
  else
     write (*,3) bottles - 1, ' bottle of beer on the wall.'
  end if
bottles = bottles - 1
  if (bottles - 1) 30, 20, 10
*    Last verse
  20 write (*,1) bottles, ' bottle of beer on the wall,'
write (*,1) bottles, ' bottle of beer.'
write (*,2) 'Take one down, pass it around...' 
write (*,4) 'No bottles of beer on the wall.'
 30 stop
end
program ninetyninebottles
integer bottles
bottles = 99

1  format (I2, A)
2  format (A)
3  format (I2, A, /)
4  format (A, /)
10 write (*,1) bottles, ' bottles of beer on the wall,'
write (*,1) bottles, ' bottles of beer.'
write (*,2) 'Take one down, pass it around...
if (bottles - 1 .gt. 1) then
 write (*,3) bottles - 1, ' bottles of beer on the wall.'
else
 write (*,3) bottles - 1, ' bottle of beer on the wall.'
end if
bottles = bottles - 1
if (bottles - 1) 30, 2

*  Last verse
20 write (*,1) bottles, ' bottles of beer on the wall,'
write (*,1) bottles, ' bottle of beer.'
write (*,2) 'Take one down, pass it around...
write (*,4) 'No bottles of beer on the wall.'
30 stop
end
data division.
file section.
* describe the input file
   fd employee-file-in
       label records standard
       block contains 5 records
       record contains 31 characters
       data record is employee-record-in.

01 employee-record-in.
   02 employee-name-in pic x(20).
   02 employee-rate-in pic 9(3)v99.
   02 employee-hours-in pic 9(3)v99.
   02 line-feed-in pic x(1).

Grace Hopper et al.
(defun gnome-doc-insert ()
  "Add a documentation header to the current function. Only C/C++ function types are properly supported currently."
  (interactive)
  (let (c-insert-here (point))
    (save-excursion
      (beginning-of-defun)
      (let (c-arglist
data-points) c-funcname
        (c-point (point))
        c-comment-point
        c-isvoid
        c-doinsert)
      (search-backward "(")
      (forward-line -2)
      (while (or (looking-at "\^\$")
                 (looking-at "\^ *\}")
                 (looking-at "\^ \\*\")
                 (looking-at "\^#"))
        (forward-line 1)))}
99 Bottles of Beer in LISP

```lisp
(defun bottles-of-bier (n)
  (case n
    (0
      '(No more bottles of beer on the wall no more bottles of beer. Go to the store and buy some more 99 bottles of beer on the wall.

    (1
      '(1 bottle of beer on the wall 1 bottle of beer. Take one down and pass it around no more bottles of beer on the wall.

    (2
      '(2 bottles of beer on the wall 2 bottles of beer. Take one down and pass it around 1 bottle of beer on the wall.

    (t
      '(',n bottles of beer on the wall ,n bottles of beer. Take one down and pass it around ,((1- n) bottles of beer on the wall.

    @(bottles-of-bier (1- n)))))
```

(defun bottles-of-bier (n)
  (case n
    (0 ' (No more bottles of beer on the wall no more bottles of beer.
      Go to the store and buy some more
      99 bottles of beer on the wall.))
    (1 ' (1 bottle of beer on the wall
      Take one down and pass it around
      no more bottles of beer on the wall.))
    (2 ' (2 bottles of beer on the wall
      Take one down and pass it around
      1 bottle of beer on the wall.))
    (t ' (n bottles of beer on the wall
      Take one down and pass it around
      (1- n) bottles of beer on the wall.
      ))))

**APL**

**Powerful operators, interactive language, custom character set**

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<table>
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<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>\texttt{Z\textasciitilde GAUSSRAND N;B;F;M;P;Q;R}</td>
</tr>
<tr>
<td>1</td>
<td>\texttt{^R}Returns ^ω random numbers having a Gaussian normal distribution</td>
</tr>
<tr>
<td>2</td>
<td>\texttt{^R} (with mean 0 and variance 1) Uses the Box–Muller method.</td>
</tr>
<tr>
<td>3</td>
<td>\texttt{^R} See Numerical Recipes in C, pg. 289.</td>
</tr>
<tr>
<td>4</td>
<td>\texttt{^R}</td>
</tr>
<tr>
<td>5</td>
<td>\texttt{Z\textasciitilde 10}</td>
</tr>
<tr>
<td>6</td>
<td>\texttt{M\textasciitilde -1+2\textasciitilde 31} \texttt{^R} largest integer</td>
</tr>
<tr>
<td>7</td>
<td>\texttt{L1:Q\textasciitilde N-PZ} \texttt{^R} how many more we need</td>
</tr>
<tr>
<td>8</td>
<td>\texttt{\rightarrow (Q\leq 0)/L2} \texttt{^R} quit if none</td>
</tr>
<tr>
<td>9</td>
<td>\texttt{Q\textasciitilde 1.3\times Q\textasciitilde K2} \texttt{^R} approx num points needed</td>
</tr>
<tr>
<td>10</td>
<td>\texttt{P\textasciitilde -1+(2\div M-1)\times -1+?(Q,2)\textasciitilde P} \texttt{^R} random points in \textasciitilde -1 to 1 square</td>
</tr>
<tr>
<td>11</td>
<td>\texttt{R++/P\times P} \texttt{^R} distance from origin squared</td>
</tr>
<tr>
<td>12</td>
<td>\texttt{B++(R\neq 0)&amp; R\leq 1}</td>
</tr>
<tr>
<td>13</td>
<td>\texttt{R+B/R &amp; P+B\neq P} \texttt{^R} points within unit circle</td>
</tr>
<tr>
<td>14</td>
<td>\texttt{F++(-2\times (R\div R)\times R)\times 5}</td>
</tr>
<tr>
<td>15</td>
<td>\texttt{Z\textasciitilde Z, P\times F, [1.5]F}</td>
</tr>
<tr>
<td>16</td>
<td>\texttt{\rightarrow L1}</td>
</tr>
<tr>
<td>17</td>
<td>\texttt{L2:Z\textasciitilde N+Z}</td>
</tr>
<tr>
<td>18</td>
<td>\texttt{^R ArchDate: 12/16/1997 16:20:23.170}</td>
</tr>
</tbody>
</table>

“Emoticons for Mathematicians”


At right: Datamedia APL Keyboard
99 Bottles of Beer in APL

(APL (A Programming Language))

Program written by JT. Taylor, www.jttaylor.net

T1←98↑[1]Ø1 99π99
T4←Ø1 98π98

T1,(98 30π’BOTTLES OF BEER ON THE WALL,‘) , T1, (98 47π’SOF BEER, TAKE ONE DOWN, PASS IT AROUND,’), T4, (98 28π’BOTTLES OF BEER ON THE WALL,’)

‘1 BOTTLE OF BEER ON THE WALL, 1 BOTTLE OF BEER, TAKE IT DOWN, PASS IT AROUND, NO BOTTLES OF BEER ON THE WALL.’

99 Bottles of Beer in APL

Iverson, IBM, 1960

Imperative, matrix-centric

E.g., perform an operation on each element of a vector

Uses own specialized character set

Concise, effectively cryptic

Primarily symbols instead of words

Dynamically typed

Odd left-to-right evaluation policy

Useful for statistics, other matrix-oriented applications

Algol, Pascal, Clu, Modula, Ada

*Imperative, block-structured language, formal syntax definition, structured programming*

PROC `insert = (INT e, REF TREE t)VOID:`

# NB inserts in t as a side effect #

IF TREE(t) IS NIL THEN
    t := HEAP NODE := (e, TREE(NIL), TREE(NIL))
ELIF e < e OF t THEN insert(e, l OF t)
ELIF e > e OF t THEN insert(e, r OF t)
FI;

PROC `trav = (INT switch, TREE t, SCANNER continue, alternative)VOID:`

# traverse the root node and right sub-tree of t only. #

IF t IS NIL THEN continue(switch, alternative)
ELIF e OF t <= switch THEN
    print(e OF t);
    traverse(switch, r OF t, continue, alternative)
ELSE # e OF t > switch #
    PROC `defer = (INT sw, SCANNER alt)VOID:`
        trav(sw, t, continue, alt);
    alternative(e OF t, defer)
FI;

Algol-68, source http://www.csse.monash.edu.au/~lloyd/tildeProgLang/Algol68/treemerge.a68
LETTHER = 'ABCDEFGHIJKLMNOPQRSTUVWXYZ$#@'
SP.CH = "+-,.=.*()'/&"
SCOTA = SP.CH
SCOTA '&' =
Q = ""
QLIT = Q FENCE BREAK(Q) Q
ELEM = QLIT | 'L' Q | ANY(SCOTA) | BREAK(SCOTA) | REM
F3 = ARBNO(ELEM FENCE)
B = (SPAN(' ') | RPOS(0)) FENCE
F1 = BREAK(' ') | REM
F2 = F1
CAOP = ('LCL' | 'SET') ANY('ABC') |
+ 'AIF' | 'AGO' | 'ACTR' | 'ANOP'
ATTR = ANY('TLSIKN')
ELEM C = '(' FENCE *F3C ')' | ATTR Q | ELEM
F3C = ARBNO(ELEM C FENCE)
ASM360 = F1 . NAME B
+ ( CAOP . OPERATION B F3C . OPERAND |
+ F2 . OPERATION B F3 . OPERAND)
+ B REM . COMMENT

Programming for the masses

10 PRINT "GUESS A NUMBER BETWEEN ONE AND TEN"
20 INPUT A$
30 IF A$ <> "5" THEN GOTO 60
40 PRINT "GOOD JOB, YOU GUESSED IT"
50 GOTO 100
60 PRINT "YOU ARE WRONG. TRY AGAIN"
70 GOTO 10
100 END

Invented at Dartmouth by John George Kemeny and Thomas Eugene Kurtz. Started the whole Bill Gates/ Microsoft thing.
The object-oriented philosophy

class Shape(x, y); integer x; integer y;
virtual: procedure draw;
begin
  comment - get the x & y coordinates -;
  integer procedure getX;
  getX := x;
  integer procedure getY;
  getY := y;

  comment - set the x & y coordinates -;
  integer procedure setX(newx); integer newx;
  x := newx;
  integer procedure setY(newy); integer newy;
  y := newy;
end Shape;
99 Bottles of Beer in Java

```java
class Bottles {
    public static void main(String args[]) {
        String s = "s";
        for (int beers=99; beers>-1;) {
            System.out.print(beers+" bottle"+s+" of beer on the wall, ");
            System.out.println(beers + " bottle" + s + " of beer, ");
            if (beers==0) {
                System.out.print("Go to the store, buy some more, ");
                System.out.println("99 bottles of beer on the wall.\n");
                System.exit(0);
            } else
                System.out.print("Take one down, pass it around, ");
            s = (--beers == 1)?"":"s";
            System.out.println(beers+" bottle"+s+" of beer on the wall.\n");
        }
    }
}
```

Sean Russell,
99 Bottles of Beer in Java

```java
class Bottles {
    public static void main(String[] args) {
        String s = "s";
        for (int beers=99; beers > -1; ) {
            System.out.print(beers + " bottle" + s + " of beer on the wall, ");
            System.out.println(beers + " bottle" + s + " of beer, ");
            if (beers == 0) {
                System.out.print("Go to the store, buy some more, ");
                System.out.println("99 bottles of beer on the wall.");
                System.exit(0);
            } else {
                System.out.print("Take one down, pass it around, ");
                s = (--beers == 1) ? "" : "s";
                System.out.println(beers + " bottle" + s + " of beer on the wall.");
            }
        }
    }
}
```

Gosling et al., Sun, 1991

- Imperative, object-oriented, threaded
- Based on C++, C, Algol, etc.
- Statically typed
- Automatic garbage collection
- Architecturally neutral
- Defined on a virtual machine (Java Bytecode)

Sean Russell,
Efficiency for systems programming

```c
int gcd(int a, int b)
{
    while (a != b) {
        if (a > b) a -= b;
        else b -= a;
    }
    return a;
}
```
#define MAXBEER 99

void chug(int beers);

int main()
{
    int beers;
    for(beers = MAXBEER; beers; chug(beers--)) ;
    puts("\nTime to buy more beer!\n");
    return 0;
}

void chug(int beers)
{
    char howmany[8], *s;
    s = beers != 1 ? "s" : "";
    printf("%d bottle%s of beer on the wall,\n", beers, s);
    printf("%d bottle%s of beeheeer . . . ,\n", beers, s);
    printf("Take one down, pass it around,\n");
    if (--beers) sprintf(howmany, "%d", beers);
    else strcpy(howmany, "No more");
    s = beers != 1 ? "s" : "";
    printf("%s bottle%s of beer on the wall.\n", howmany, s);
}
#define MAXBEER 99

void chug(int beers);

int main()
{
    int beers;
    for(beers = MAXBEER; beers > 0;)
        puts("\nTime to buy more beer!");
    return 0;
}

void chug(int beers)
{
    char howmany[8], *s;
    s = beers != 1 ? "s" : "";
    printf("%d bottle%s of beer on the wall,
", beers, s);
    printf("%d bottle%s of beer . . . ,
", beers, s);
    printf("Take one down, pass it around,
");
    if (--beers)
        sprintf(howmany, "%d", beers);
    else
        strcpy(howmany, "No more");
    s = beers != 1 ? "s" : "";
    printf("%s bottle%s of beer on the wall.
", howmany, s);
}

Dennis Ritchie, Bell Labs, 1969

Procedural, imperative

Based on Algol, BCPL

Statically typed; liberal conversion policies

Harmonizes with processor architecture

For systems programming: unsafe by design

Remains language of choice for operating systems

Functional languages with types and syntax

```haskell
structure RevStack = struct
  type 'a stack = 'a list
  exception Empty
val empty = []
fun isEmpty (s:'a stack):bool = 
  (case s
    of [] => true
    | _  => false)
fun top (s:'a stack): =
  (case s
    of [] => raise Empty
    | x::xs => x)
fun pop (s:'a stack):'a stack =
  (case s
    of [] => raise Empty
    | x::xs => xs)
fun push (s:'a stack,x: 'a):'a stack = x::s
fun rev (s:'a stack):'a stack = rev (s)
end
```
99 Bottles of Beer in Haskell

```haskell
bottles :: Int -> String
bottles n
    | n == 0 = "no more bottles"
    | n == 1 = "1 bottle"
    | n > 1  = show n ++ " bottles"

verse :: Int -> String
verse n
    | n == 0 = "No more bottles of beer on the wall, "
        ++ "no more bottles of beer.\n"
        ++ "Go to the store and buy some more, "
        ++ "99 bottles of beer on the wall."
    | n > 0  = bottles n ++ " of beer on the wall, "
        ++ bottles n
        ++ " of beer.\n"
        ++ "Take one down and pass it around, "
        ++ bottles (n-1) ++ " of beer on the wall.\n"

main = mapM (putStrLn . verse) [99,98..0]
```

Simon Johansson,
```haskell
bottles :: Int -> String
bottles n
| n == 0 = "no more bottles"
| n == 1 = "1 bottle"
| n > 1 = show n ++ " bottles"

verse :: Int -> String
verse n
| n == 0 = "No more bottles of beer on the wall, 
++ "no more bottles of beer."
++ "Go to the store and buy some more, 
++ "99 bottles of beer on the wall."
| n > 0 = bottles n ++ " of beer on the wall, 
++ bottles n ++ " of beer."
++ "Take one down and pass it around, 
++ bottles (n-1) ++ " of beer on the wall."

main = mapM (putStrLn . verse) [99,98..0]
```

Peyton Jones et al., 1990

Functional

Pure: no side-effects

Lazy: computation only on demand; infinite data structures

Statically typed; types inferred

Algebraic data types, pattern matching, lists, strings

Great for compilers, domain-specific languages, type system research

Related to ML, OCaml

Simon Johansson,
Scripting languages: glue for binding the universe together

```sh
class() {
    classname='echo "$1" | sed -n '1 s/ */.*$//p'
    parent='echo "$1" | sed -n '1 s/^.*: *///p'
    hppbody='echo "$1" | sed -n '2,$p'

    forwarddefs="$forwarddefs
    class $classname;

    if (echo $hppbody | grep -q "$classname()"); then
        defaultconstructor=
    else
        defaultconstructor="$classname() {}"
    fi
}
```
99 Bottles of Beer in AWK

BEGIN {
    for (i = 99; i >= 0; i--) {
        print ubottle(i), "on the wall," , lbottle(i) "."
        print action(i), lbottle(inext(i)), "on the wall."
        print
    }
}

function ubottle(n) {
    return sprintf("%s bottle%s of beer", n?n:"No more", n-1?"s"="")
}

function lbottle(n) {
    return sprintf("%s bottle%s of beer", n?n:"no more", n-1?"s"="")
}

function action(n) {
    return sprintf("%s", n ? "Take one down and pass it around," : "Go to the store and buy some more,"
    "Go to the store and buy some more," )
}

function inext(n) {
    return n ? n - 1 : 99
}

OsamuAoki,
99 Bottles of Beer in AWK

BEGIN {
    for (i = 99; i >= 0; i--) {
        print ubottle(i), "on the wall,", lbottle(i) " ."
        print action(i), lbottle(inext(i)), "on the wall."
        print
    }
}

function ubottle(n) {
    return sprintf("%s bottle%s of beer", n ? n : "No more", n ? n - 1 ? "s" : "")
}

function lbottle(n) {
    return sprintf("%s bottle%s of beer", n ? n : "no more", n ? n - 1 ? "s" : "")
}

function action(n) {
    return sprintf("%s", n ? "Take one down and pass it around," : "Go to the store and buy some more,")
}

function inext(n) {
    return n ? n - 1 : 99
}

Aho, Weinberger, and Kernighan, Bell Labs, 1977

Interpreted domain-specific scripting language for text processing

Pattern-action statements matched against input lines

C-inspired syntax

Automatic garbage collection

OsamuAoki,
AWK (bottled version)

Wilhelm Weske,
for quant in range(99, 0, -1):
    if quant > 1:
        print quant, "bottles of beer on the wall," , \
        quant, "bottles of beer."
    if quant > 2:
        suffix = str(quant - 1) + " bottles of beer on the wall."
    else:
        suffix = "1 bottle of beer on the wall."
    elif quant == 1:
        print "1 bottle of beer on the wall, 1 bottle of beer."
        suffix = "no more beer on the wall!"
        print "Take one down, pass it around," , suffix
    print ""

Gerold Penz,
for quant in range(99, 0, -1):
    if quant > 1:
        print quant, "bottles of beer on the wall,", quant, "bottles of beer."
        if quant > 2:
            suffix = str(quant - 1) + " bottles of beer on the wall."
        else:
            suffix = "1 bottle of beer on the wall."
    else:
        suffix = "1 bottle of beer on the wall, 1 bottle of beer."
        print """Take one down, pass it around,"
        print """no more beer on the wall!"

Gerold Penz,
99 Bottles of Beer in FORTH

: .bottles ( n -- n-1 )
  dup 1 = IF ." One bottle of beer on the wall," CR
  ." One bottle of beer," CR
  ." Take it down,"
  ELSE dup ." bottles of beer on the wall," CR
  dup ." bottles of beer," CR
  ." Take one down,"
  THEN
  CR
  ." Pass it around," CR
  1-

?dup IF dup 1 = IF ." One bottle of beer on the wall;"
  ELSE dup ." bottles of beer on the wall;"
  THEN
  ELSE ." No more bottles of beer on the wall." THEN

THEN
  CR

;

: nbottles ( n -- )
BEGIN .bottles ?dup NOT UNTIL ;

99 nbottles

Dan Reish,
99 Bottles of Beer in FORTH

: .bottles ( n -- n-1 )
  dup 1 = IF ." One bottle of beer on the wall,"
    ." One bottle of beer,"
    ." Take it down,"
  ELSE dup ." bottles of beer on the wall,"
    dup ." bottles of beer,"
    ." Take one down,"
    ." Pass it around,"
  THEN
  CR ." Pass it around,"
  CR 1-
  ?dup IF dup 1 = IF ." One bottle of beer on the wall;"
    ELSE dup ." bottles of beer on the wall;"
    THEN
    ELSE ." No more bottles of beer on the wall."
    THEN
  CR
;

: nbottles ( n -- )
BEGIN .bottles ?dup NOT
99 nbottles

Moore, NRAO, 1973

Stack-based imperative language

Trivial, RPN-inspired grammar

Easily becomes cryptic

Untyped

Low-level, very lightweight

Highly extensible: easy to make programs compile themselves

Used in some firmware boot systems (Apple, IBM, Sun)

Inspired the PostScript language for laser printers

Dan Reish,
The Whitespace Language

Edwin Brady and Chris Morris, April 1st, 2003

Imperative, stack-based language

Space, Tab, and Line Feed characters only

Number literals in binary: Space=0, Tab=1, LF=end

Less-than-programmer-friendly syntax; reduces toner consumption

Andrew Kemp, http://compsoc.dur.ac.uk/whitespace/
VisiCalc, Lotus 1-2-3, Excel

The spreadsheet style of programming

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>ITEM</td>
<td>NO.</td>
<td>UNIT</td>
<td>COST</td>
</tr>
<tr>
<td>MUCK RAKE</td>
<td>43</td>
<td>12.95</td>
<td>556.85</td>
</tr>
<tr>
<td>BUZZ CUT</td>
<td>15</td>
<td>6.75</td>
<td>101.25</td>
</tr>
<tr>
<td>TOE TONER</td>
<td>250</td>
<td>49.95</td>
<td>12487.50</td>
</tr>
<tr>
<td>EYE SNUFF</td>
<td>2</td>
<td>4.95</td>
<td>9.90</td>
</tr>
</tbody>
</table>

| SUBTOTAL | 13155.50 |
| TOTAL    | 14438.16 |

VisiCalc on the Apple II, c. 1979
CREATE TABLE shirt (  
id SMALLINT UNSIGNED NOT NULL AUTO_INCREMENT,  
style ENUM('t-shirt', 'polo', 'dress') NOT NULL,  
color ENUM('red', 'blue', 'white', 'black') NOT NULL,  
owner SMALLINT UNSIGNED NOT NULL  
    REFERENCES person(id),  
PRIMARY KEY (id)  
);  

INSERT INTO shirt VALUES  
(NULL, 'polo', 'blue', LAST_INSERT_ID()),  
(NULL, 'dress', 'white', LAST_INSERT_ID()),  
(NULL, 't-shirt', 'blue', LAST_INSERT_ID());
> SELECT * FROM users WHERE clue > 0
0 rows returned
99 Bottles of Beer in SQL

```sql
SELECT
  CASE (bottlecount)
    WHEN 0 THEN 'No more bottle of beer on the wall, no more bottles of beer on the wall. ' ||
      'Go to the store and buy some more, 99 bottles of beer on the wall.'
    WHEN 1 THEN '1 bottle of beer on the wall, 1 bottle of beer. ' ||
      'Take one down and pass it around, no more bottles of beer on the wall.'
    WHEN 2 THEN '2 bottles of beer on the wall, 2 bottles of beer. ' ||
      'Take one down and pass it around, 1 bottle of beer on the wall.'
  ELSE rtrim (cast((BottleCount) as char(2))) || ' bottles of beer on the wall, ' ||
      rtrim (cast((BottleCount) as char(2))) || ' bottles of beer. ' ||
      rtrim (cast((BottleCount)-1 as char(2))) || ' bottles of beer on the wall.'
  END
FROM
  (SELECT avalue * 10 + bvalue as bottlecount
   FROM
     (VALUES (9), (8), (7), (6), (5), (4), (3), (2), (1), (0)) a(avalue)
     (VALUES (9), (8), (7), (6), (5), (4), (3), (2), (1), (0)) b(bvalue)
  ) as valuelist;
```

Kent Olsen,
SELECT  
  CASE (bottlecount)  
      WHEN 0 THEN  'No more bottle of beer on the wall, no more bottles of beer. '  
                      'Go to the store and buy some more, 99 bottles of beer.'  
      WHEN 1 THEN  '1 bottle of beer on the wall, 1 bottle of beer. '  
                      'Take one down and pass it around, no more bottles of beer.'  
      WHEN 2 THEN  '2 bottles of beer on the wall, 2 bottles of beer. '  
                      'Take one down and pass it around, 1 bottle of beer on the wall.'  
      ELSE  
          rtrim (cast((BottleCount) as char(2))) || ' bottles of beer on the wall, '  
          rtrim (cast((BottleCount)-1 as char(2))) || ' bottles of beer. '  
          'Take one down and pass it around, '  
          rtrim (cast((BottleCount)-2 as char(2))) || ' bottles of beer on the wall.'  
  END  
FROM  
  (  
      SELECT  avalue * 10 + bvalue  
      FROM  
          (VALUES (9), (8), (7), (6), (5), (4), (3), (2), (1), (0)) as a(avalue),  
          (VALUES (9), (8), (7), (6), (5), (4), (3), (2), (1), (0)) as b(bvalue)  
  ) as valuelist;

Chamberlin and Boyce, IBM, 1974
Declarative language for databases
Semantics based on the relational model
Queries on tables: select with predicates, joining, aggregating
Database query optimization: declaration to procedure

Kent Olsen,
Prolog

Logic Language

\[
\begin{align*}
\text{witch}(X) & \iff \text{burns}(X) \land \text{female}(X). \\
\text{burns}(X) & \iff \text{wooden}(X). \\
\text{wooden}(X) & \iff \text{floats}(X). \\
\text{floats}(X) & \iff \text{sameweight}(\text{duck}, X).
\end{align*}
\]

\[
\begin{align*}
\text{female}(\text{girl}). \quad \{ \text{by observation} \} \\
\text{sameweight}(\text{duck}, \text{girl}). \quad \{ \text{by experiment} \}
\end{align*}
\]

? \text{witch}(\text{girl}).
99 Bottles of Beer in Prolog

```prolog
bottles :-
    bottles(99).

bottles(1) :-
    write('1 bottle of beer on the wall, 1 bottle of beer,\'), nl,
    write('Take one down, and pass it around,\'), nl,
    write('Now they are all gone.'), nl, !.

bottles(X) :-
    write(X), write(' bottles of beer on the wall,\'), nl,
    write(X), write(' bottles of beer,\'), nl,
    write('Take one down and pass it around,\'), nl,
    NX is X - 1,
    write(NX), write(' bottles of beer on the wall.'), nl, nl,
    bottles(NX).
```

Remko Trocon et al.,
99 Bottles of Beer in Prolog

\[
\text{bottles} :- \\
\quad \text{bottles}(99).
\]

\[
\text{bottles}(1) :- \\
\quad \text{write}('1 bottle of beer on the wall, 1 bottle of beer,') \\
\quad \text{nl} \\
\quad \text{write}('Take one down, and pass it around,') \\
\quad \text{nl} \\
\quad \text{write}('Now they are all gone.') \\
\quad \text{nl},!
\]

\[
\text{bottles}(X) :- \\
\quad \text{write}(X), \text{write}(' bottles of beer on the wall,') \\
\quad \text{nl} \\
\quad \text{write}(X), \text{write}(' bottles of beer,') \\
\quad \text{nl} \\
\quad \text{write}('Take one down and pass it around,') \\
\quad \text{nl} \\
\quad NX \text{ is } X - 1, \\
\quad \text{write}(NX), \text{write}(' bottles of beer on the wall.') \\
\quad \text{nl} \\
\quad \text{nl} \\
\quad \text{bottles}(NX).
\]

Alain Colmerauer et al., 1972
Logic programming language

Programs are relations: facts and rules

Program execution consists of trying to satisfy queries

Designed for natural language processing, expert systems, and theorem proving

Remko Trocon et al.,