Programming Languages and Translators

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Prof. Stephen A. Edwards and Prof. Baishakhi Rey also teach 4115.

*These slides are borrowed from Prof. Edwards.

What is a Programming Language?

A programming language is a notation that a person and a computer can both understand.

- It allows you to express what is the **task** to compute
- It allows a computer to **execute** the computation task

Every programming language has a **syntax** and **semantics**.

- Syntax: how characters combine to form a program
- Semantics: what the program *means*

Components of a language: Syntax

How characters combine to form a program.

Calculate the n-th Fibonacci number.

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

```
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:

$$
\begin{array}{rcl}
\mathit{expr} & \rightarrow & \mathit{expr} + \mathit{expr} \\
& | & \mathit{expr} - \mathit{expr} \\
& | & \mathit{expr} * \mathit{expr} \\
& | & \mathit{expr} \,/\, \mathit{expr} \\
& | & (\ \mathit{expr}\ ) \\
& | & \textbf{digits}
\end{array}
$$

Components of a language: Semantics

What a well-formed program "means."

The semantics of C says this computes the nth Fibonacci number.

```
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;
}
```

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:

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

Ambiguous in Java:

```
class Bar {
  public float foo() { return 0; }
  public int foo() { return 0; }
}
```

What is a Translator?

A programming language is a notation that a person and a computer can both understand.

- It allows you to express what is the **task** to compute
- It allows a computer to **execute** the computation task

A translator translates what you express to what a computer can execute.

What is a Translator?

C

```
int gcd(int a, int b)
{
  while (a != b) {
    if (a > b)
      a -= b;
    else b -= a;
  }
  return a;
}
```

Assembly

```
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
```

Bytes

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

Course Structure

Course Structure

Course home page:
https://www.cs.columbia.edu/ rgu/courses/4115/spring2019

26 Lectures: Mondays and Wednesdays, 2:40 – 3:55 PM

Jan 22 – May 4

451 CSB

Team project report	May 13
Midterm Exam	Mar 11
Final Exam (in class)	May 4

3 Assignments

Assignments and Grading

40%	Team Programming Project
20%	Midterm Exam
20%	Final Exam (cumulative)
20%	Three individual homework assignments

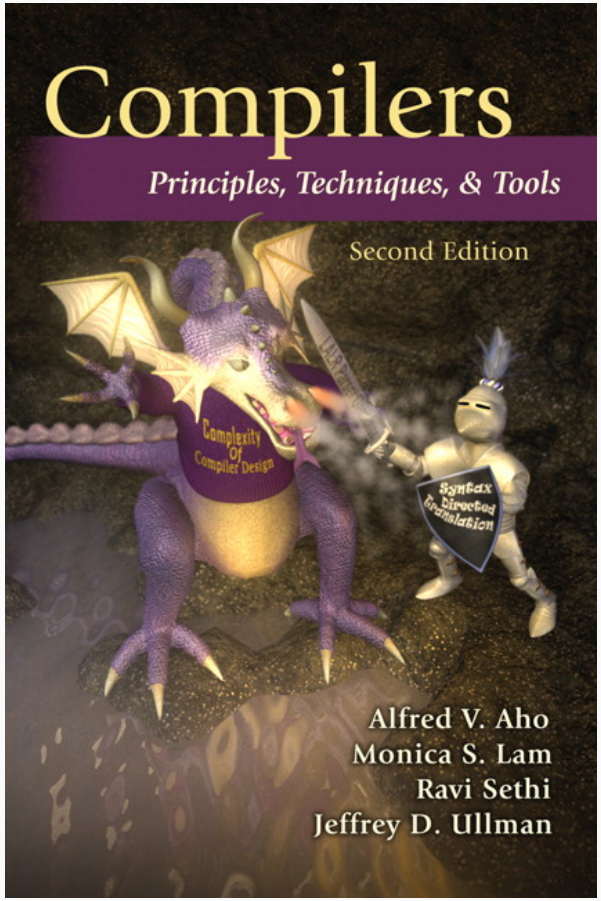
Team project is most important, but most students do well on it. Grades for tests often vary more.

Recommended Text

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

Compilers: Principles, Techniques, and Tools.

Addison-Wesley, 2006.
Second Edition.



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

Read the CS Department's Academic Honesty Policy:
https://www.cs.columbia.edu/education/honesty/

Collaborate with your team on the project.

Do your homework by yourself.

- OK: Discussing lecture content, OCaml features
- Not OK: Solving a homework problem with classmates
- Not OK: Posting any homework questions or solutions

Don't be a cheater (e.g., copy from each other)

The Team Project

The Team Project

Bid over a list of project ideas of language design and compiler implementation.

Four deliverables:

1. A proposal describing your plan (due Feb 26)
2. A milestone: a minimum viable product (due Mar 30)
3. A compiler component, written in OCaml (due May 13)
4. A final project report (due May 13)

Teams

Immediately start forming four-person teams (3 to 5)

Each teach member should participate in design, coding, testing, and documentation

Role	Responsibilities
Manager	Timely completion of deliverables
Language Guru	Language design
System Architect	Compiler architecture, development environment
Tester	Test plan, test suites

START EARLY!

How Do You Work In a Team?

- 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

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

3. Select a weekly meeting time
   Harder than you might think

Project Proposal

- Describe the project that you plan to implement.
- Describe roles of each team member.
- Describe the road map.
- 1–2 pages

Final Report Sections

Section	Author
Introduction	Team
Reference Manual	Team
Language Evolution	Language Guru
Translator Architecture	System Architect
Test plan and scripts	Tester
Conclusions	Team

Project Due Dates

Proposal	Feb 26 soon
MVP	Mar 30
Final Report and Code Submission	May 13

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
```

FORTRAN

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
     jne   .L7
.L9: leave
     ret
.L5: subl  %eax, %edx
     jmp   .L2
```

After: Expressions, control-flow

```
10    if (a .EQ. b) goto 20
      if (a .LT. b) then
         a = a - b
      else
         b = b - a
      endif
      goto 10
20    end
```

FO

Backus, IBM, 1956

Imperative language for science and engineering

First compiled language

Fixed format punch cards

Arithmetic expressions, If, Do, and Goto statements

Scalar and array types

Limited string support

Still common in high-performance computing

Inspired most modern languages, especially BASIC

B

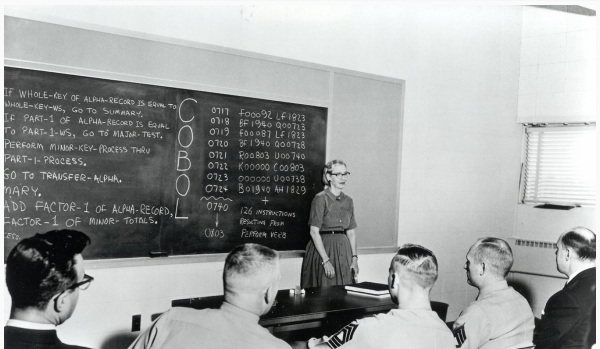
After: Expressions, control-flow

```
10    if (a .EQ. b) goto 20
      if (a .LT. b) then
         a = a - b
      else
         b = b - a
      endif
      goto 10
20    end
```

COBOL

Added type declarations, record types, file manipulation

```
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).
```



English-like syntax: 300 reserved words

Grace Hopper et al.

LISP, Scheme, Common LISP

Functional, high-level languages

```
(defun append (l1 l2)
  (if (null l1)
      l2
      (cons (first l1) (append (rest l1) l2))))
```

LISP, Scheme, Common LISP

Functional, high-level langu

```
(defun append (l1 l2)
  (if (null l1)
      l2
      (cons (first l1)
```

McCarthy, MIT, 1958

Functional: recursive, list-focused functions

Semantics from Church's Lambda Calculus

Simple, heavily parenthesized S-expression syntax

Dynamically typed

Automatic garbage collection

Originally for AI applications

Dialects: Scheme and Common Lisp

APL

Powerful operators, interactive, custom character set

```
[0]    Z←GAUSSRAND N;B;F;M;P;Q;R
[1]    ⍝Returns ⍵ random numbers having a Gaussian normal distribution
[2]    ⍝ (with mean 0 and variance 1)  Uses the Box-Muller method.
[3]    ⍝ See Numerical Recipes in C, pg. 289.
[4]    ⍝
[5]    Z←⍳0
[6]    M←¯1+2*31          ⍝ largest integer
[7]   L1:Q←N-⍴Z           ⍝ how many more we need
[8]    →(Q≤0)/L2          ⍝ quit if none
[9]    Q←⌈1.3×Q÷2         ⍝ approx num points needed
[10]   P←¯1+(2÷M-1)×¯1+?(Q,2)⍴M  ⍝ random points in -1 to 1 square
[11]   R←+/P×P            ⍝ distance from origin squared
[12]   B←(R≠0)∧R<1
[13]   R←B/R ⋄ P←B⌿P      ⍝ points within unit circle
[14]   F←(¯2×(⊛R)÷R)*.5
[15]   Z←Z,,P×F,[1.5]F
[16]   →L1
[17]  L2:Z←N↑Z
[18]   ⍝ ArchDate: 12/16/1997 16:20:23.170
```

“Emoticons for Mathematicians”

Source: Jim Weigang, http://www.chilton.com/~jimw/gsrand.html

At right: Datamedia APL Keyboard

APL

Powerful operators, interactive, custom character set

```
[0]    Z←GAUSSRAND N;B;F;M;P;Q;R
[1]    ⍝Returns ⍵ random numbers
[2]    ⍝ (with mean 0 and varian
[3]    ⍝ See Numerical Recipes i
[4]    ⍝
[5]    Z←⍳0
[6]    M←¯1+2*31          ⍝ largest
[7]   L1:Q←N-⍴Z           ⍝ how mar
[8]    →(Q≤0)/L2          ⍝ quit if
[9]    Q←⌈1.3×Q÷2         ⍝ approx
[10]   P←¯1+(2÷M-1)×¯1+?(Q,2)⍴M
[11]   R←+/P×P            ⍝ distanc
[12]   B←(R≠0)∧R<1
[13]   R←B/R ⋄ P←B⌿P      ⍝ points
[14]   F←(¯2×(⍟R)÷R)*.5
[15]   Z←Z,,P×F,[1.5]F
[16]   →L1
[17]  L2:Z←N↑Z
[18]   ⍝ ArchDate: 12/16/1997 16
```

“Emoticons for Mathematician

Source: Jim Weigang, http://www.chilton.com/~jim

At right: Datamedia APL Keyboard

- 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);
```

String-processing languages

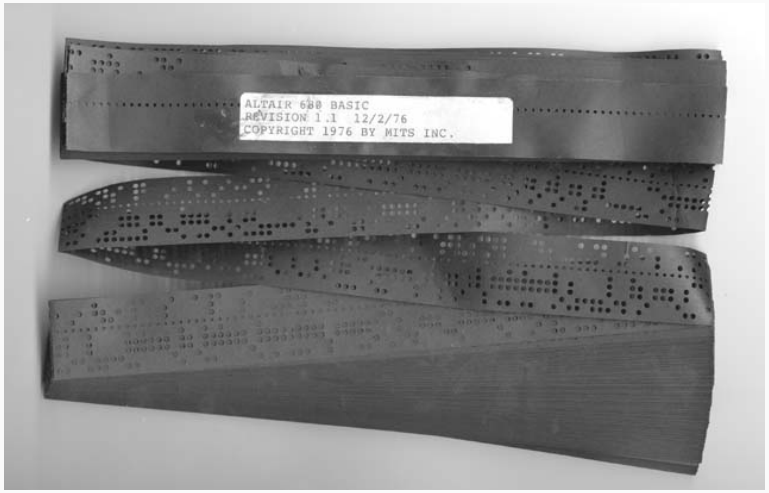
```
  LETTER = 'ABCDEFGHIJKLMNOPQRSTUVWXYZ$#@'
  SP.CH  = "+-,=.*()'/& "
  SCOTA  = SP.CH
  SCOTA  '&' =
  Q  =  "'"
  QLIT  =  Q  FENCE  BREAK(Q)  Q
  ELEM  =  QLIT | 'L' Q | ANY(SCOTA) | BREAK(SCOTA) | REM
  F3  =  ARBNO(ELEM FENCE)
  B  =  (SPAN(' ') | RPOS(0))  FENCE
  F1  =  BREAK(' ')  |  REM
  F2  =  F1
  CAOP  =  ('LCL'  |  'SET')  ANY('ABC')  |
+  'AIF'  |  'AGO'  |  'ACTR'  |  'ANOP'
  ATTR  =  ANY('TLSIKN')
  ELEMC  =  '(' FENCE *F3C ')'  |  ATTR Q  |  ELEM
  F3C  =  ARBNO(ELEMC  FENCE)
  ASM360  =  F1 . NAME  B
+  ( CAOP . OPERATION  B  F3C . OPERAND  |
+  F2 . OPERATION  B  F3 . OPERAND)
+  B  REM . COMMENT
```

BASIC

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

```
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 wa
      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
    }
  }
}
```

Sean Russell, http://www.99-bottles-of-beer.net/language-java-4.html

99 Bottles of Beer in Java

```
class Bottles {
  public static void mai
    String s = "s";
    for (int beers=99; b
      System.out.print(b
      System.out.println
      if (beers==0) {
        System.out.print
        System.out.print
        System.exit(0);
      } else
        System.out.print
      s = (--beers == 1)
      System.out.println
    }
  }
}
```

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, http://www.99-bottles-of-beer.net/language-java-4.html

Efficiency for systems programming

```
int gcd(int a, int b)
{
  while (a != b) {
    if (a > b) a -= b;
    else b -= a;
  }
  return a;
}
```

C

Efficiency for systems progr

```
int gcd(int a, int b)
{
  while (a != b) {
    if (a > b) a -= b;
    else b -= a;
  }
  return a;
}
```

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

```
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.

99 Bottles of Beer in Haskell

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

verse :: Int -> String
verse n
  | n == 0 = "No more bo
             ++ "no more
             ++ "Go to t
             ++ "99 bott
  | n > 0  = bottles n +
             ++ bottles
             ++ " of bee
             ++ "Take on
             ++ bottles

main       = mapM (putStr
```

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

Scripting languages: glue for binding the universe together

```
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?
}
function lbottle(n) {
    return sprintf("%s bottle%s of beer", n?n:"no more", n-1?
}
function action(n) {
    return sprintf("%s", n ? "Take one down and pass it aroun
                           "Go to the store and buy some mo
}
function inext(n) {
    return n ? n - 1 : 99
}
```

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 bo
}
function lbottle(n) {
    return sprintf("%s bo
}
function action(n) {
    return sprintf("%s",

}
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

AWK (bottled version)

```
        split( \
        "no mo"\
        "rexxN"\
        "o mor"\
        "exsxx"\
        "Take "\
      "one dow"\
    "n and pas"\
   "s it around"\
  ", xGo to the "\
"store and buy s"\
"ome more, x bot"\
"tlex of beerx o"\
"n the wall" , s,\
"x"); for( i=99 ;\
i>=0; i--){ s[0]=\
s[2] = i ; print \
s[2 + !(i) ] s[8]\
s[4+ !(i-1)] s[9]\
s[10]", " s[!(i)]\
s[8] s[4+ !(i-1)]\
s[9]".";i?s[0]--:\
s[0] = 99; print \
s[6+!i]s[!(s[0])]\
s[8] s[4 +!(i-2)]\
```

Wilhelm Weske,
http://www.99-bottles-of-beer.net/language-awk-1910.html

99 Bottles of Beer in Python

```
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
        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,
http://www.99-bottles-of-beer.net/language-python-808.html

99 Bottles of Beer in Python

```
for quant in range(99, 0, -1):
    if quant > 1:
        print quant, "bott
              quant, "bott
        if quant > 2:
            suffix = str(qu
        else:
            suffix = "1 bo
    elif quant == 1:
        print "1 bottle of
        suffix = "no more
    print "Take one down,
    print ""
```

Guido van Rossum, 1989

Object-oriented, imperative

General-purpose scripting language

Indentation indicates grouping

Dynamically typed

Automatic garbage collection

Gerold Penz,
http://www.99-bottles-of-beer.net/language-python-808.html

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

99 nbottles
```

99 Bottles of Beer in FORTH

```
: .bottles ( n -- n-1 )
   dup 1 = IF   ." One bo
                ." One bo
                ." Take i
   ELSE  dup . ." bottle
         dup . ." bottle
         ." Take one dow
   THEN
   CR
   ." Pass it around," C
   1-
   ?dup IF   dup 1 = IF
             ELSE  dup .
             THEN
        ELSE   ." No more
   THEN
   CR
;
: nbottles ( n -- )
  BEGIN  .bottles  ?dup

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[41]

The Whitespace Language

Edwin Brady and Chris Morris, April 1st, 2003

Imperative, stack-based language

Space, Tab, and Line Feed characters only

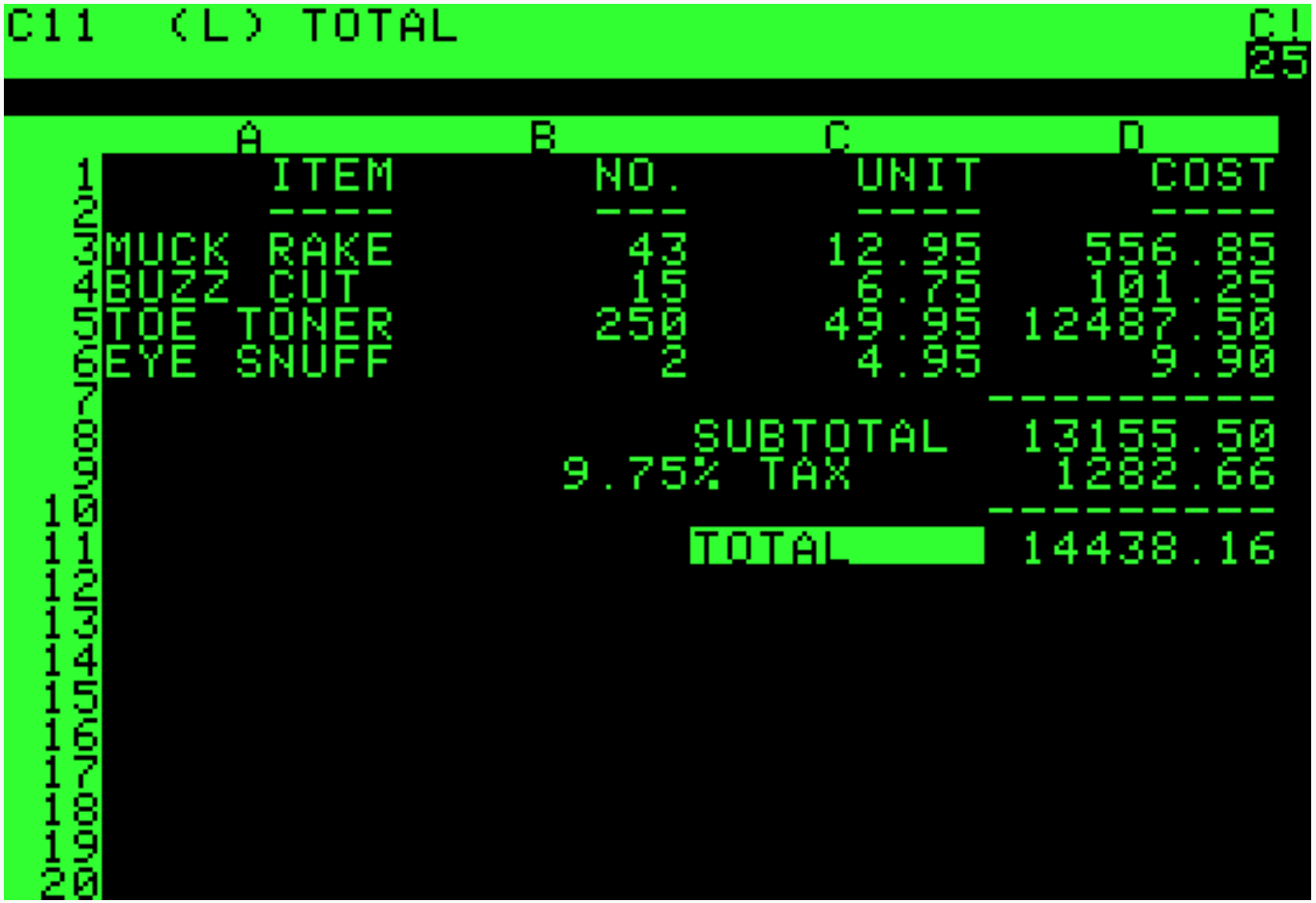
Number literals in binary: Space=0, Tab=1, LF=end

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



Visicalc on the Apple II, c. 1979

Database queries

```
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());
```

Database queries

```
CREATE TABLE shirt (
      id SMALLINT UNSIGNE
      style ENUM('t-shirt
      color ENUM('red', '
      owner SMALLINT UNSIG
            REFERENCES pe
     PRIMARY KEY (id)
);

INSERT INTO shirt VALUE
(NULL, 'polo', 'blue', 
(NULL, 'dress', 'white'
(NULL, 't-shirt', 'blue
```

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

Logic Language

```
witch(X)   <= burns(X), female(X).
burns(X)   <= wooden(X).
wooden(X)  <= floats(X).
floats(X)  <= sameweight(duck, X).

female(girl).              {by observation}
sameweight(duck,girl).     {by experiment }

? witch(girl).
```

Prolog

Logic Language

```
witch(X)  <= burns(X), female(X).
burns(X)  <= wooden(X).
wooden(X) <= floats(X).
floats(X) <= sameweight

female(girl).
sameweight(duck, girl).

? witch(girl).
```

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