• Essential component of “high-level” languages.

• Most familiar for arithmetic operators.

• Abstract away from precise order of evaluation, naming of intermediate results.

\[
x1 = \frac{(-b + \sqrt{b^2 - 4ac})}{2a}
\]

\[
t1 = -b \\
t2 = b^2 \\
t3 = 4a \\
t4 = t3 \cdot c \\
t5 = t2 - t4 \\
t6 = \sqrt{t5} \\
t7 = t1 + t6 \\
t8 = 2 \cdot a \\
t9 = t7/t8
\]

• Issue: Precedence rules (handled in parsing).

• Issue: Mixed-mode expressions and implicit coercions.
Many languages extend “high-level” expression facility to non-arithmetic values, such as booleans.

- **Operands:** `true`, `false`, boolean-valued variables.
- **Operators:** `and`, `or`, `not`.

Booleans are typically a separate type (C/C++ is an exception).

Key issue: Does language use **short-circuit** evaluation for boolean expressions?

- `a AND b`: evaluate `b` only if `a` evaluates to `true`.
- `a OR b`: evaluate `b` only if `a` evaluates to `false`.

```plaintext
if (x < 7 || costly(y) > 6) ...
if (p != NULL && p->x > 7) ...
```

Common misuse of booleans:

```plaintext
BOOLEAN flag;
flag := IF (x < 2) THEN true ELSE false;
```
Some languages support expressions over larger values, e.g., vector, strings, etc.

```c
int a[10], b[10], c[10];
c := a * 5 + b;

C: for (i = 0; i < 10; i++)
   c[i] = a[i] * 5 + b[i];

string a, b, c;
a := b & substring(c,2,4);

C: char *a,*b,*c;
   int n = max(strlen(c)-2,4);
a = malloc(strlen(b) + n + 1);
strncpy(a,b);
strncpy(a+strlen(b),c+2,n);
a[strlen(b)+n] = '\0';
```
Most languages allow function calls (with appropriate return type) to appear within expressions. So we can build expressions over an arbitrary type, just by defining an appropriate set of functions.

However, function call syntax is typically inflexible. Many languages let us use new infix operators as a special way of denoting functions.

- Operator syntax, precedence, etc. may be fixed for language or programmer-definable.
- Issues like sharing, storage management are tricky.
- Not all operators act like functions.
STATEMENT-LEVEL CONTROL STRUCTURES

- Sequencing
- Selection
- Iteration

(• Concurrency)

Primary mechanisms developed in FORTRAN and ALGOL60; mostly minor changes since then (40+ years).

We distinguish control “structures” from “structureless” code using goto’s and indirect jumps (“spaghetti code”).

Concurrent computation may be more “natural” (for neurons and hardware) but appears hard to reason about accurately!
MACHINE-LEVEL CONTROL FLOW

- Sequencing; unless otherwise directed, do the next instruction.
- Labels, i.e., addresses in target code.
- Unconditional GOTOs.
- Arithmetic and logical IF \(?\) THEN GOTO constructs.

These more than suffice to compute anything that can be computed (as best we know).
(e.g., Edsger Dijkstra, “Go to statement considered harmful,” *CACM*, 11(3), March 1968, 147-148.)

Branches (conditional and unconditional) suffice to program anything; they are what machines use.

BUT problems are **best** solved in terms of higher-level constructs, such as loops and conditional blocks.

- Program text should make programmer’s intent **explicit**.
- Static structure of program text should **resemble** dynamic structure of program execution.

Undisciplined use of GOTO’s makes these goals hard to achieve.

(Not just “GOTOs are bad.”)
“Single-entry, single-exit.”

Loops:

```plaintext
while <condition> loop
  <statements>
end loop
```

Can also put test at end. Sometimes want it in the middle...

```plaintext
loop
  <statements>
  exit if <condition>;
  <statements>
end loop
```

Using `exit` violates single-exit goal. If loops are nested, want ability to `exit` any number of levels.
FOR LOOPS

for i in <lower-bound>..<upper-bound> loop
    <statements>
end loop

Common questions:

• When are bounds calculated? Are they recalculated?
• Can <statements> change value of i
• Does i have a defined value after the end loop?
• Can one jump into or out of loop?
• What if upper-bound is less than lower-bound to start with?

C example:

    for (i = *p; i > 0; i--)

can be optimized better than

    for (i=1; i <= *p; i++)
We can give recursive definitions to the meaning of iterative statements.

Example:

```plaintext
while <condition> do <statements>
```

is equivalent to

```plaintext
if <condition> then
    begin
    <statements>;
    while <condition> do <statements>
    end
```

Any iteration can be converted to a recursion.

The converse is not true in general. But any tail-recursion (such as the one above) can be converted into an iteration. Any decent compiler should take advantage of this (though many don’t).
CONDITIONALS AND CASES

if <condition> then
  <statements>
elsif < condition> then
  <statements>
elsif ...
else
  <statements>
endif

(Various parts can be missing.)

case <expression> of
  <value1>: <statements>
  <value2>: <statements>
  ...
  otherwise: <statements>
end case

Permits more efficient code (a jump table) if values are “dense.”

That’s All, Folks! This set of statements suffices for nearly all programs.
Completely unrestricted jumps are seldom allowed.

It makes little sense to allow jumps into the middle of a block, since none of the block-local storage will have been properly initialized.

Many languages permit jumps out to enclosing blocks; in a stack allocation scheme, such jumps require quietly popping one or more frames.

Most languages provide special forms of escapes from structured program components, such as loop exit.

These discourage uses of goto, but some good uses remain.
Problem: Given a key value \( k \), search an array \( a \) for a matching entry and increment the corresponding element of an array \( b \). If not found, add the new key to the end of \( a \).

A solution with \texttt{goto} (in C):

```c
int i;
for (i = 0; i < n; i++)
    if (a[i] == k)
        goto found;
    n++;
    a[i] = k;
    b[i] = 0;
found:
    b[i]++;
```
A SOLUTION WITH BOOLEANS (IN JAVA):

```java
boolean found = false;
int i = 0;
while (i < n && !found) {
    if (a[i] == k)
        found = true;
    else
        i++;
}
if (!found) {
    n = i;
    a[i] = k;
    b[i] = 0;
}
    b[i]++;
This is clumsier and slower.
```
A SOLUTION WITH ONE-LEVEL EXIT (IN JAVA):

```java
boolean found = false;
int i;
for (i = 0; i < n; i++) {
    if (a[i] == k) {
        found = true;
        break;
    }
}
if (!found) {
    i = n;
    n++;
    a[i] = k;
    b[i] = 0;
}
    b[i]++;

This is better, but still requires testing \texttt{found} below the loop.
```
A solution with multi-level exit (in Java):

In Java (unlike C/C++), we can `break` from any named enclosing block.

```java
int i;
search:
{ for (i = 0; i < n; i++)
    if (a[i] == k)
        break search;
    n++;
    a[i] = k;
    b[i] = 0;
}
    b[i]++;
```

This does the trick. How is it better than the original `goto` version?
THE COME FROM STATEMENT

10 J = 1
11 COME FROM 20
12 PRINT J
   STOP
13 COME FROM 10
20 J = J + 2


But is this really a joke?

Even with a GO TO, we must examine both the branch and the target label to understand the programmer’s intent.
Problem: Sending characters to an output device as quickly as possible.

Given:

```c
char p[] = "hello world...";
char *m = p;
int n = ... /* length of p */
#define output(c) ... /* do output */
```

Solution 1:

```c
for (i = 0; i < n; i++)
    output(*m++);
```

Or (a little simpler if we are allowed to destroy n):

```c
while(n--)
    output(*m++);
```
Faster to **unroll** loop, say 4 times:

```c
while (n & 3) {
    output(*m++);
    --n;
}
```

```c
n /= 4;
if (n) do { output (*m++);
            output (*m++);
            output (*m++);
            output (*m++);
        } while (--n);
```

Or (the **Duff Loop**):

```c
i = (n+3)/4;
if (n) switch (n & 3) {
    case 0: do {output(*m++);
                output(*m++);
                output(*m++);
                output(*m++);
            } while (--i);
    }
```
Exceptions

Programs often need to handle exceptional conditions, i.e., deviations from “normal” control flow.

Exceptions may arise from

- failure of built-in or library operations (e.g., division by zero, end of file)
- user-defined events (e.g., key not found in dictionary)

Awkward or impossible to deal with these conditions explicitly without distorting normal code.

Most recent languages (Ada, C++, Java, etc.) provide a means to define, raise, and handle exceptions.
EXAMPLE: EXCEPTIONS IN JAVA

class Help extends Exception {}
try {
... if (gone wrong) throw new Help();
... x = a / b; ...
} catch (Help e) {
    ...report problem...
} catch (ArithmeticException e) {
    x = -99;
}
WHAT TO DO IN AN EXCEPTION?

If there is a statically enclosing handler, the thrown exception behaves much like a `goto`. In previous example:

```plaintext
...  
  if (gone wrong) goto help_label;
  ..
  help_label: ...report problem...
```

But what if there is no handler explicitly wrapped around the exception-throwing point?

- In most languages, uncaught exceptions **propagate** to next **dynamically** enclosing handler. E.g., caller can handle uncaught exceptions raised in callee.
- Many languages permit a value to be returned along with the exception itself.
- A few languages support **resumption** of the program at the point where the exception was raised.
class BadThing extends Exception {

int foo () {
    ... throw new BadThing(); ... 
}

bar () {
    int x;
    try {
        x = foo ();
    } catch (BadThing e) {
        x = 0;
    }
}

Implementation of dynamic exception handling requires integration with function call/return mechanism.