Computer Systems 1
Lecture 11

Records and Pointers

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Topics

Compilation patterns

- We have looked at several high level programming constructs
  - if b then S
  - if b then S else S
  - while b do S
  - for $var := exp$ to exp do S
- There is a standard way to translate each to low level form: assignment, goto L, if b then goto L
- The low level statements correspond closely to instructions

Follow the patterns!

You should use these patterns as you write your programs because

- This helps you understand *precisely* what high level language constructs mean—this is one of the aims of the course.
- This is essentially how real compilers work, and this is another aim of the course.
- This saves time because
  - It's quicker to catch errors at the highest level (e.g. translating if-then-else to goto) rather than the lowest level (instructions)
  - It makes the program more readable, and therefore faster to check and to debug
- This leads to good comments that make the program more readable
- This approach scales up to large programs
- Experienced programmers recognise the patterns, so if you use them your code is easier to read and debug and maintain

How can you tell if you're using the pattern?

- Each pattern contains
  - Changeable parts: boolean expressions, integer expressions, statements
  - Fixed parts: goto, if-then-goto
  - The labels have to be different every time, but the structure of the fixed parts never changes
- Example: translating a while loop
  - There should be one comparison, one conditional jump at the start of the loop
  - There should be one unconditional jump at the end of the loop

Are you using the pattern?

High level code:

```
while bexp do
    S
```

The pattern for translation to low level:

```
label1
    if bexp = False then goto label2
    S
    goto label1
label2
```

- The blue text is fixed (except you need to use unique labels)
- There should be one comparison, one conditional jump at the start of the loop
- There should be one unconditional jump at the end of the loop

Can you gain efficiency by violating the pattern?

- No! Example: avoid the cost of jumping to a test that jumps out of the loop by transforming the while loop to

```
label1
    if bexp = False then goto label2
label3
    S
    if bexp = True then goto label3
label2
```

- But consider:
  - Even if the loop executes a million times, this version saves *at most* one jump instruction
  - And the code is longer, which likely makes it slower (because of cache—haven't reached that topic yet)
  - And when you do this in a large program it becomes incomprehensible
  - Aim for readability and correctness

Comments

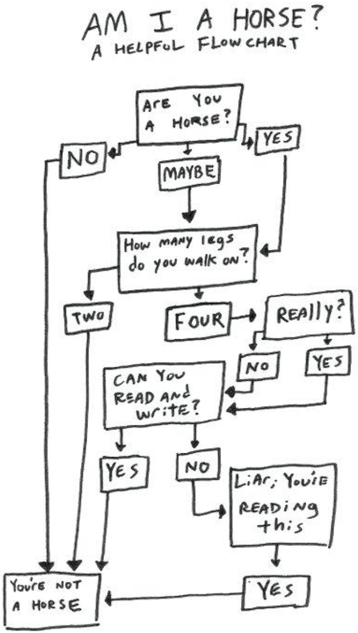
- Initial comments to identify the program, author, date
- Early comments to say what the program does
- High level algorithm (in comments)
- Translation to low level algorithm (in comments)
- Translation to assembly language (with comments)
    - Copy the low level algorithm comments, and paste, so you have two copies
    - The first copy remains as the low level algorithm
    - In the second copy, insert the assembly language code
    - Every low level statement should appear as a comment in the assembly code

Write the comments first!

- The program development methodology entails writing the comments *first*
- Avoid the temptation of writing code first, hacking it until it appears to work, and then adding comments
- The comments, the high and low level algorithms, *help you to get it correct!*

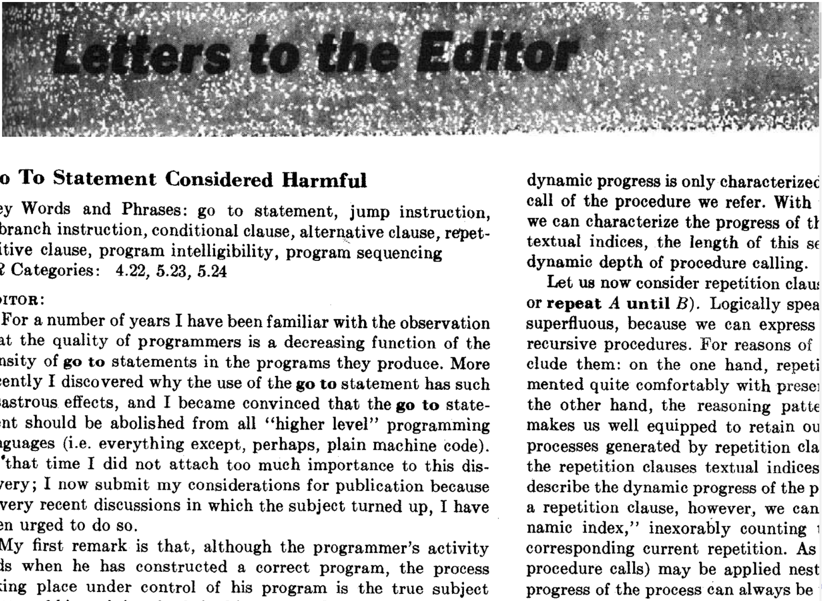
Why is goto controversial?

- If you develop code randomly, with goto jumping all over the place, the program is hard to understand, unlikely to work, and difficult to debug
- This has given the goto statement a bad reputation
- But goto is *essential* for a compiler because it's essentially the jump instruction
- The compilation patterns provide a *safe* and *systematic* way to introduce goto into a program
- But if you ignore the patterns, you lose these advantages
- Unstructured goto leads to complicated code


AM I A HORSE?
A HELPFUL FLOWCHART
Are You A Horse?
NO
MAYBE
YES
How many legs do you walk on?
TWO
FOUR
Really?
NO
YES
CAN YOU READ AND write?
YES
NO
Liar; You're READING this
YES
You're NOT A HORSE

Edsger Dijkstra

Goto considered harmful: *CACM* **11**(3), March 1968



Letters to the Editor

Go To Statement Considered Harmful

Key Words and Phrases: go to statement, jump instruction, branch instruction, conditional clause, alternative clause, repetitive clause, program intelligibility, program sequencing
CR Categories: 4.22, 5.23, 5.24

EDITOR:

For a number of years I have been familiar with the observation that the quality of programmers is a decreasing function of the density of **go to** statements in the programs they produce. More recently I discovered why the use of the **go to** statement has such disastrous effects, and I became convinced that the **go to** statement should be abolished from all "higher level" programming languages (i.e. everything except, perhaps, plain machine code). At that time I did not attach too much importance to this discovery; I now submit my considerations for publication because in very recent discussions in which the subject turned up, I have been urged to do so.

My first remark is that, although the programmer's activity ends when he has constructed a correct program, the process taking place under control of his program is the true subject

dynamic progress is only characterized
call of the procedure we refer. With
we can characterize the progress of th
textual indices, the length of this se
dynamic depth of procedure calling.

Let us now consider repetition clau
or **repeat** *A* **until** *B*). Logically spea
superfluous, because we can express
recursive procedures. For reasons of
clude them: on the one hand, repeti
mented quite comfortably with prese
the other hand, the reasoning patte
makes us well equipped to retain ou
processes generated by repetition cla
the repetition clauses textual indices
describe the dynamic progress of the p
a repetition clause, however, we can
namic index," inexorably counting
corresponding current repetition. As
procedure calls) may be applied nest
progress of the process can always be

What happened next?

- Considered harmful
  - Dozens (hundreds?) of *X considered harmful* essays
- Goto elimination
  - Theorem: *every* program using goto can be expressed without goto, using while and if-then-else
- Structured programming
  - A positive, effective way to develop programs (instead of focusing on eliminating goto)

goto

I COULD RESTRUCTURE THE PROGRAM'S FLOW
OR USE ONE LITTLE 'GOTO' INSTEAD.
EH, SCREW GOOD PRACTICE. HOW BAD CAN IT BE?
goto main_sub3;
COMPILE

https://xkcd.com/292/

Records

A record contains several fields. Access a field with the dot (.) operator

```
;   x, y :
;     record
;       { fieldA : int;
;         fieldB : int;
;         fieldC : int;
;       }
;
;   x.fieldA := x.fieldB + x.fieldC;
;   y.fieldA := y.fieldB + y.fieldC;
```

(Some programming languages call it a tuple or struct.)

Defining some records

```
; Data definitions

; The record x
x
x_fieldA   data   3     ; offset 0 from x  &x_fieldA = &x
x_fieldB   data   4     ; offset 1 from x  &x_fieldB = &x + 1
x_fieldC   data   5     ; offset 2 from x  &x_fieldC = &x + 2

; The record y
y
y_fieldA   data  20     ; offset 0 from y  &y_fieldA = &y
y_fieldB   data  21     ; offset 1 from y  &y_fieldB = &y + 1
y_fieldC   data  22     ; offset 2 from y  &y_fieldC = &y + 2
```

Naming each field explicitly

```
; ----------------------------------------------------------------------
; Simplistic approach, with every field of every record named
; explicitly

; In record x,  fieldA := fieldB + fieldC

; x.fieldA := x.fieldB + x.fieldC
   load   R1,x_fieldB[R0]
   load   R2,x_fieldC[R0]
   add    R1,R1,R2
   store  R1,x_fieldA[R0]
```

This is awkward—but there's a better way!

Pointers

So far, we have been finding a piece of data by giving it a label

```
     load    R2,xyz[R0]
...
xyz  data  5
```

An alternative way to find the data is to make a pointer to it

A pointer is an address

&x means the address of x: a pointer to x. You can apply the & operator to a variable but not to a complex expression

- &x is ok
- &(3*x) is not ok

*p means the value that p points to. You can apply the * operator to any pointer.

Expressions using pointers

- The & operator gives the address of its operand
  - p := x puts the *value* of x into p
  - p := & x puts the *address* of x into p. The address of x is called a *pointer to* x, and we say "p points at x".
- The * operator follows a pointer and gives whatever it points to
  - *p is an expression whose value is whatever p points at
  - y := p stores p into y, so y is also now a pointer to x
  - y := *p *follows the pointer* p, gets the value (which is x) and stores that in y

The & operator requires only one instruction: lea!

```
     lea   R5,x[R0]     ; R5 := &x
...
     lea   R6,y[R0]     ; R6 := &y
     store R6,p[R0]     ; p := &y
...
x    data  25
y    data  0
p    data  0
```

The * operator requires only one instruction: load!

```
load   R7,p[R0]     ; R7 := p
load   R8,0[R7]     ; R8 := *p
```

Flexibility of load and lea

We have now seen two ways to use lea:

- To load a constant into a register: lea R1,42[R0] ; R1 := 42
- To create a pointer: lea R2,x[R0] ; R2 := &x
- lea can do more, too — can you figure out what?

And there are several ways to use load:

- To load a variable into a register: load R3,x[R0] ; R3 := x
- To access an array element: load R4,a[R5] ; R4 := a[R5]
- To follow a pointer: load R6,0[R7] ; R6 := *R7

Following a pointer to the address of x gives x

The value of `*(&x)` is just `x`!

```
lea     R4,x[R0]     ; R4 := &x
load    R5,0[R4]     ; R5 := *(&x) = x

load    R6,x[R0]     ; R6 := x
```

Review: accessing a variable the ordinary way

Low level language (same as high level)

```
x := x + 5;
```

Assembly language

```
; Accessing variable x by its address, with R0
     lea     R1,5[R0]     ; R1 := 5 (constant)
     load    R2,x[R0]     ; R2 := x
     add     R2,R2,R1     ; R2 := x + 5
     store   R2,x[R0]     ; x := x + 5
```

Accessing a variable through a pointer

Low level language (same as high level)

```
x := x + 5;
```

Assembly language

```
; Put a pointer to x into R3, which contains the address of x
; R3 := &x
    lea     R3,x[R0]      ; R3 := &x

; Add 5 to whatever word R3 points to
    lea     R1,5[R0]      ; R1 := 5 (constant)
    load    R4,0[R3]      ; R4 := *R3
    add     R4,R4,R1      ; R4 := *R3 + 5
    store   R4,0[R3]      ; *R3 := *R3 + 5
```

Equivalent to `*(&x) := *(&x) + 5`

Why is the pointer helpful?

- We can write a block of code that accesses variables through pointers.
- This can be *reused*, by executing it with the pointer set to point to different data.
- Later, we'll see additional benefits of using pointers.

Access a record using a pointer

```
; Make the same code work for any record with the same fields

; Set x as the current record by making R3 point to it
   lea     R3,x[R0]     ; R3 := &x

; Perform the calculation on the record that R3 points to
   load    R1,1[R3]     ; R1 := (*R3).fieldB
   load    R2,2[R3]     ; R2 := (*R3).fieldC
   add     R1,R1,R2     ; R1 := (*R3).fieldB + (*R3).fieldC
   store   R1,0[R3]     ; *R3.fieldA := (*R3).fieldB + (*R3).fi
```

Requests to the Operating System

- Many operations cannot be performed directly by a user program because
  - (Main reason): user could violate system security
  - Also, some operations are difficult to program
  - The code would need to change when OS is updated
- The program requests the operating system to perform them
- An OS request is performed by executing a `trap` instruction, such as `trap R1,R2,R3`
- A trap is a jump to the Operating System (and you don't have to give the address to jump to)
- We use pointers to tell the operating system what to do

Typical OS requests

- The type of request is a number, placed in R1, and operands (if any) are in R2, R3
- The specific codes used to make a request are defined by the operating system, not by the hardware
- This is a major reason why compiled programs run only on one operating system
- Typical requests:
  - Terminate execution of the program
  - Read from a file
  - Write to a file
  - Allocate a block of memory

Termination

- A program cannot stop the machine; it requests the operating system to terminate it
- The operating system then removes the program from its tables of running programs, and reclaims any resources dedicated to the program
- In Sigma16, you request termination by `trap R0,R0,R0`

Character strings: pointer to array of characters

- A string like `The cat in the hat` is represented as an array of characters
- Each element of the array contains one character
- If you are writing a string to output, the last character of the string should be a “newline character”

Write operation on Sigma16

To write a string of characters

- trap R1,R2,R3
- R1 — 2 is the code that indicates a write request
- R2 — address of first word of string to write
- R3 — length of string (the last word should be newline character)
- See example program Write.asm.txt

Writing a string

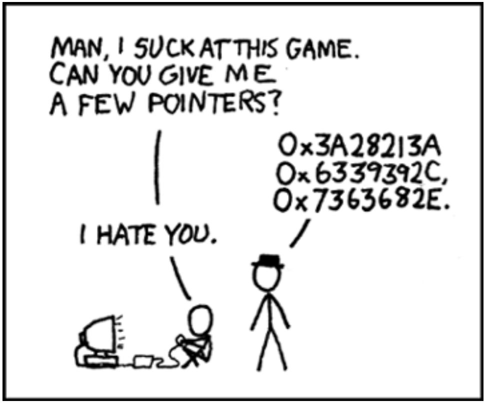
To write a string named out, we use (1) lea to load a constant, (2) lea to load the address of an array, (3) load to get a variable

```
; write out (size = k)
     lea    R1,2[R0]         ; trap code: write
     lea    R2,animal[R0]    ; address of string to print
     load   R3,k[R0]         ; string size = k
     trap   R1,R2,R3         ; write out (size = k)

     trap   R0,R0,R0         ; terminate

k    data   4    ; length of animal
; animal = string "cat"
animal
     data   99   ; character code for 'c'
     data   97   ; character code for 'a'
     data  116   ; character code for 't'
     data   10   ; character code for newline
```

pointers



https://xkcd.com/138/