What Happened On Canvas?

- Late Wednesday, the pages for ECS 150 on Canvas disappeared.
- I chatted with the Canvas folks (on the phone, wait time was very long).
- They suggested I try something, I did, and it didn't work.
- They escalated the problem, and around noon it got fixed.
- What happened?
  - Apparently when a new section was added, the ECS 150 pages on Canvas were re-initialized
  - The folks to whom the problem was escalated were able to put everything back (phew!)

New Section Is Opened

- The new section was approved late Wednesday
- It’s in 55 Roessler on Wednesday from 1:10pm to 2:00pm
- Please do not ask me if you will get in; I don’t know
  - I do know that graduating seniors in CS and ECS will have priority
- If you would prefer to go to the other discussion section, whichever one it is, you can just go and sit in if there is an empty seat
- Changing sections using a PTA has lots of problems

Interprocess Synchronization and Communication

What’s the Problem?

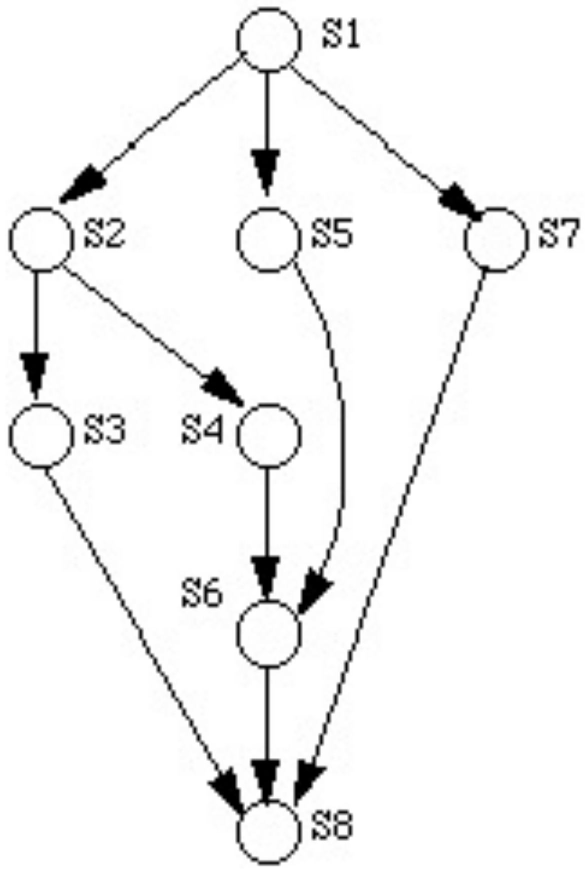
- Processes executing simultaneously
  - Multiple cores or CPUs
  - Process uses the GPU or FPU for computation
- Some statements must be completed before others are begun

```
a ← x + y
b ← z + 1
c ← a + b
d ← c + 1
```

- Here, the first two statements *must* be executed before the third or fourth (precedence constraint)
- But the first two can be done independently

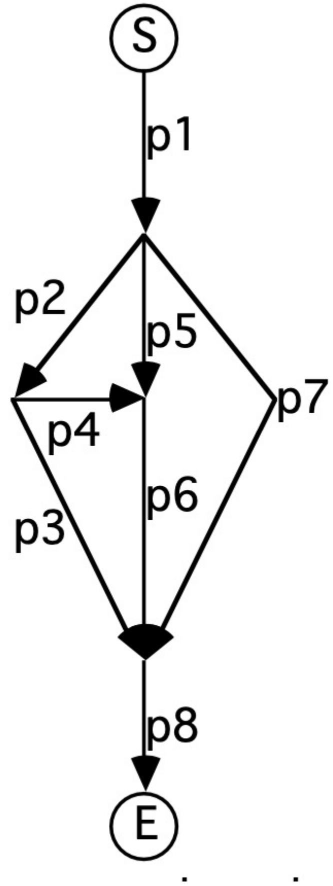
Precedence, Process Flow Graphs

Precedence graph



- Precedence graph focuses on *statements*
- Process flow graph focuses on *processes*
- Both must be acyclic graphs
- And, they are equivalent

Process flow graph



Bernstein Conditions

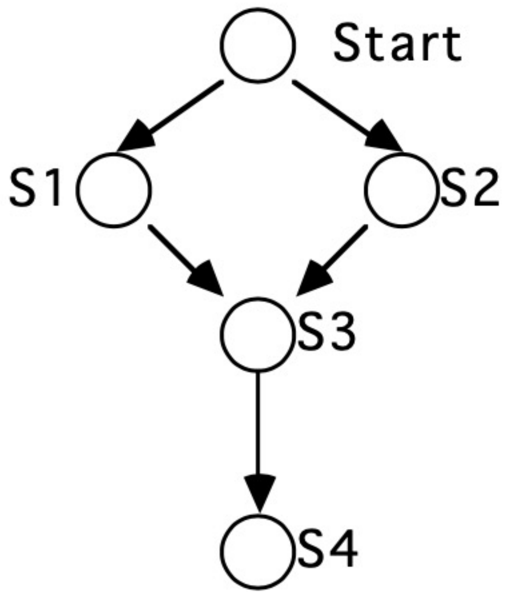
- Describe when statements can be executed in parallel
- $R(S_i)$: set of variables that are read in statement S_i
- $W(S_i)$: set of variables that are written in statement S_i
- Bernstein conditions for statements S_i and S_j:

$$R(S_i) \cap W(S_j) = \emptyset \text{ and } R(S_j) \cap W(S_i) = \emptyset \text{ and } W(S_i) \cap W(S_j) = \emptyset$$

Bernstein Conditions

- Remember this?

```
a ← x + y
b ← z + 1
c ← a + b
d ← c + 1
```



- In the above example:

$R(S_1) = \{ x, y \}$ $R(S_2) = \{ z \}$ $R(S_3) = \{ a, b \}$ $R(S_4) = \{ c \}$

$W(S_1) = \{ a \}$ $W(S_2) = \{ b \}$ $W(S_3) = \{ c \}$ $W(S_4) = \{ d \}$

- As $W(S_1) \cap R(S_3) = \{ \text{a} \} \neq \emptyset$, 1 and 3 must be executed sequentially.
- As $R(S_1) \cap W(S_2) = \emptyset$ and $R(S_2) \cap W(S_2) = \emptyset$ and $W(S_1) \cap W(S_2) = \emptyset$, 1 and 2 can be executed in parallel

Parallel Programming: *fork*, *join*, *quit*

- *fork L*
  - Split process in two; first begins after the fork, second begins at *L*

  Example:

```
   fork L
   a ← x+y;
   . . .
L: b ← z + 1
```

- *join count, L*
  - Decrement *count* and if 0, branch to *L*

  In other words:

```
count ← count - 1
if count = 0 then
     goto L
```

Example

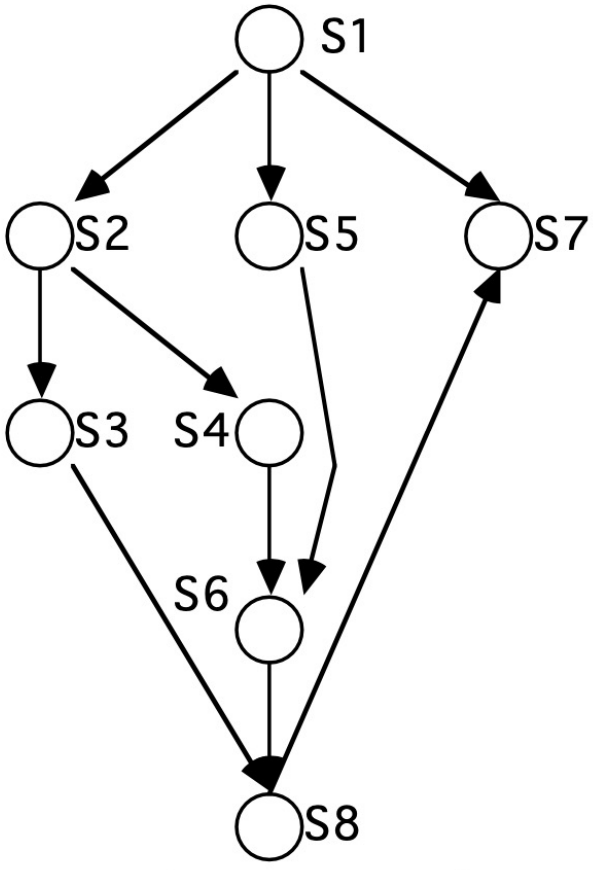
```
        count ← 2;
        fork dopar
        a ← x + y;
        goto endpar
dopar:  b ← z + 1;
endpar: join count, next
        quit
next:   c ← a – b
        d ← c + 1
```

- This computes:

```
a ← x + y
b ← z + 1
c ← a + b
d ← c + 1
```

with the first two lines executing in parallel, and then after those the last two lines execute sequentislly

More Complicated Example




```
    t6 ← 2;
    t8 ← 3;
    S1; fork p2; fork p5; fork p7;
p2: S2; fork p3; fork p4; quit
p5: S5; join t6,p6; quit;
p7: S7; join t8,p8; quit;
p3: S3; join t8,p8; quit;
p4: S4; join t6,p6; quit;
p6: S6; join t8,p8; quit;
p8: S8; quit;
```

Comments

- Advantages
  - simple
  - powerful
  - easy to derive from precedence or process flow graphs
- Disadvantages
  - clumsy
  - lots of gotos and goto-like structures

parbegin, parend

- These bracket statements or blocks to be done in parallel
- Eliminates gotos and goto-like structures
- Example:

```
parbegin
    a ← x + y
    b ← z + 1
parend
c ← a − b;
d ← c + 1
```

Comments

- Advantages
  - easy to read
  - uses principles of modular programming
  - avoids goto-like structures
- Disadvantages
  - not as powerful as the *fork-join-quit* primitives

Why?

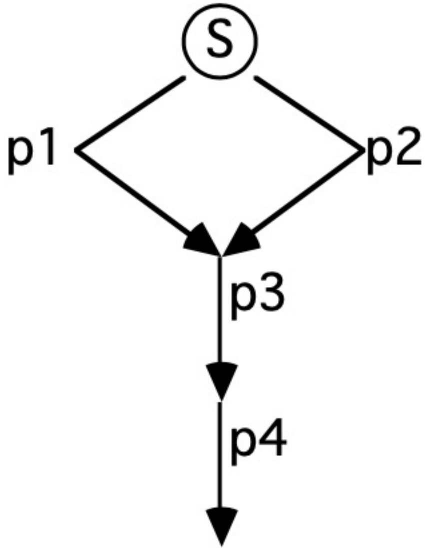
- Consider the concept of proper nesting
- *S*(*a*, *b*): represents serial execution of processes *a*, *b*
- *P*(*a*, *b*): represents parallel execution of processes *a*, *b*
- A process flow graph is *properly nested* if it can be described by *P*, *S*, and functional composition

Example of Proper Nesting

- The program

```
parbegin
   a ← x + y
   b ← z + 1
parend
c ← a − b;
d ← c + 1
```

The process flow graph

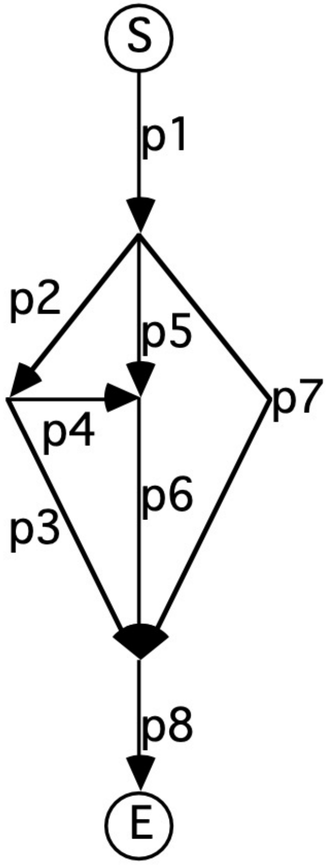


The functional representation

P(a, b)
S(P(a, b), c)
S(S(P(a, b), c)), d)

So it is properly nested

Another Example



CLAIM: This is not properly nested

PROOF: For something to be properly nested, it must ne of the form $S(p_i, p_j)$ or $P(p_i, p_j)$ at most interior level.

It's not $P(p_i, p_j)$ as there are no constructs of that form in the graph.

All serially connected processes p_i, p_j have at least 1 more process p_k starting or finishing at the node n_{ij} between p_i and p_j; but if $S(p_i, p_j)$ is the innermost level, there cannot be any such pk, because if it existed, another, more interior *P* or *S* must be present, contradiction. So it's not $S(p_i, p_j)$ either.

What This Means

- *fork*, *join*, *quit* can represent more complex structures than *parbegin* and *parent*
- *parbegin*, *parend* require the process flow graph to be properly nested

The Problem with Process Interaction

- Consider the following implementation of the *producer-consumer problem*
- One process (producer) generates items that it must pass to the other process (consumer)
  - Consumer must wait for the producer to produce an item
  - Producer must not produce more items when buffer is full
- Sometimes called the *bounded buffer problem*

The Problem with Process Interaction

- The variables
  - `buffer` and `counter` are shared variables
  - `counter` can assume values between 0 and n inclusive

```
var buffer: array [0..n-1] of item;
in, out: 0...n-1;
counter: 0...n
```

Producer and Consumer Code

- Producer code

```
producer:
repeat
      make next p;
      while counter = n do
            (* nothing *);
      buffer[in] ← next p;
      in ← (in+1) mod n;
      counter ← counter + 1;
until false;
```

- Consumer code

```
consumer:
repeat
      while counter = 0 do
            (* nothing *);
      next ← buffer[out];
      out ← (out + 1) mod n
      counter ← counter - 1;
until false;
```

Does It Work In Parallel?

- Suppose counter is 5, and consider the lines counter ⟵ counter + 1 and counter ⟵ counter – 1.
- They could compile into the following:

counter = counter + 1:	counter ⟵ counter – 1:
P1: r1 ⟵ counter	C1: r2 ⟵ counter
P2: r1 ⟵ r1 + 1	C2: r2 ⟵ r2 – 1
P3: counter ⟵ r1	C3: counter ⟵ r2

A Race Condition

- Depending on how the statements intermingle, you get different values for count

- P1 P2 C1 C2 P3 C3 counter is 4
- P1 P2 P3 C1 C2 C3 counter is 5
- P1 P2 C1 C2 C3 P3 counter is 6

Critical Section Problem

- Critical section: block of code that only one process at a time can execute
  - When one process is in its critical section, no other process can be in its corresponding critical section
- *Problem*: design a protocol to do this
- *Generic description of solution framework*:

  entry section

  critical section

  exit section

  remainder section

Requirements for Solution

- *Mutual Exclusion*: at most 1 process can be in the critical section at any time
- *Progress*: if no process is in the critical section, and several other processes wish to enter, then only processes not in the remainder section can take part in deciding which process enters
- *Bounded Wait*: a bound on the number of times other processes are allowed to enter the critical section after a process asks to enter the critical section and before it is allowed to

Implicit assumption: each process runs at non-zero speed, but *no assumption is made as to relative speed*

Background

- We use 2 processes, p_i and p_j
- Either $i = 0$ and $j = 1$ or $j = 0$ and $i = 1$
- Current process is always p_i and the other one is p_j

- First, we'll analyze several proposed solutions

Proposed Solution 1

```
var turn: 0..1;      // whose turn it is
while turn ≠ i do         // … entry section
     /* nothing */
. . .                // … critical section
turn = j;            // … exit section
```

Proposed Solution 1 Analysis

- Mutual exclusion? Yes; turn can only have 1 value, and second line blocks the process that does not have that value from entering critical section
- Progress? No; processes *must* enter the critical section in alternate order; so a process in the remainder section takes part in deciding which process enters the critical section

Proposed Solution 2

```
var inCS: array[0..1] of boolean = false;
                    // who is in critical section
while inCS[j] do    // … entry section
     /* nothing */
inCS[i] = true
. . .               // … critical section
inCS[i] = false;    // … exit section
```

Proposed Solution 2 Analysis

- Mutual Exclusion: No; suppose p_i, p_j execute the while statement at the same time. As both `inCS[i]` and `inCS[j]` are `false`, both enter the critical section.

Proposed Solution 3

```
var interested: array[0..1] of boolean = false;
               // who wants to enter critical section
interested[i] = true;     // … entry section
while interested[j] do
     /* nothing */
. . .                    // … critical section
interested[i] = false;   // … exit section
```

Proposed Solution 3 Analysis

- Mutual Exclusion: Yes; a process cannot enter the critical section unless `interested[j]` is `false` but if a process is in the critical section, `interested[j]` must be `true`.
- Progress: No; suppose both processes arrive at the `while` statement at the same time; as both elements of `interested[]` are true, they loop forever

Proposed Solution 4

```
var interested: array[0..1] of boolean = false;
               // who wants to enter critical section
turn: 0..1;
interested[i] = true;     // … entry section
turn = j;
while interested[j] and turn = j do
     /* nothing */
. . .                    // … critical section
interested[i] = false;   // … exit section
```

Proposed Solution 4 Analysis

- Mutual Exclusion: Yes. p_i enters the critical section only if `interested[j]` is `false` and `turn` is *i*. For p_i, p_j both to be in the critical section, both elements of `interested[]` must be `true`. Only one could have passed the while loop (as turn is *i* or *j* but not both) so one does the loop (say, p_j) and the other does the preceding lines. After the first line in entry section, both elements of `interested[]` are `true`, but `turn` is *j*, so only p_j enters the critical section. So only 1 process can be in the critical section at a time.

Proposed Solution 4 Analysis

- Progress: Yes. p_i blocked from entering critical section only if it is stuck at the `while` loop, which means `interested[j]` is true and `turn` is *j*. If p_j is not in the entry or critical sections, `interested[j]` is false and p_i goes in.
  If p_j is at the `while` statement, `turn` is either *i* or *j*, and the process with index turn will go in. Once p_i leaves the critical section, `interested[i]` is false and p_j can go in. If p_j resets `interested[j]` to true, then turn is set to *i* and p_i goes in. So only processes in the entry, exit, or critical section affect which process goes in, demonstrating progress.
- Bounded wait: Yes. At most one additional entry by p_j will occur if both request entry at the same time, so the wait is bounded.