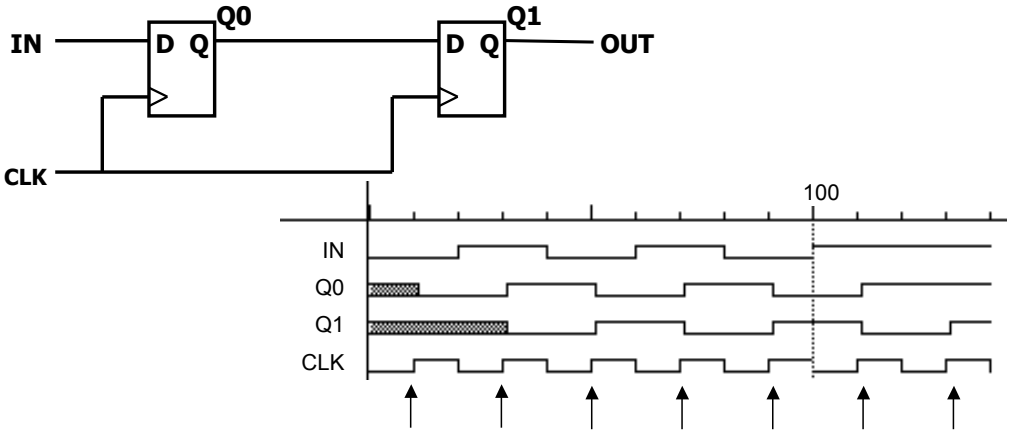
Controller Implementation--Part I

- Alternative controller FSM implementation approaches based on:
  - Classical Moore and Mealy machines
  - Time state: Divide and Counter
  - Jump counters
  - Microprogramming (ROM) based approaches
    - » branch sequencers
    - » horizontal microcode
    - » vertical microcode

Cascading Edge-triggered Flip-Flops

- Shift register
  - New value goes into first stage
  - While previous value of first stage goes into second stage
  - Consider setup/hold/propagation delays (prop must be > hold)



Cascading Edge-triggered Flip-Flops

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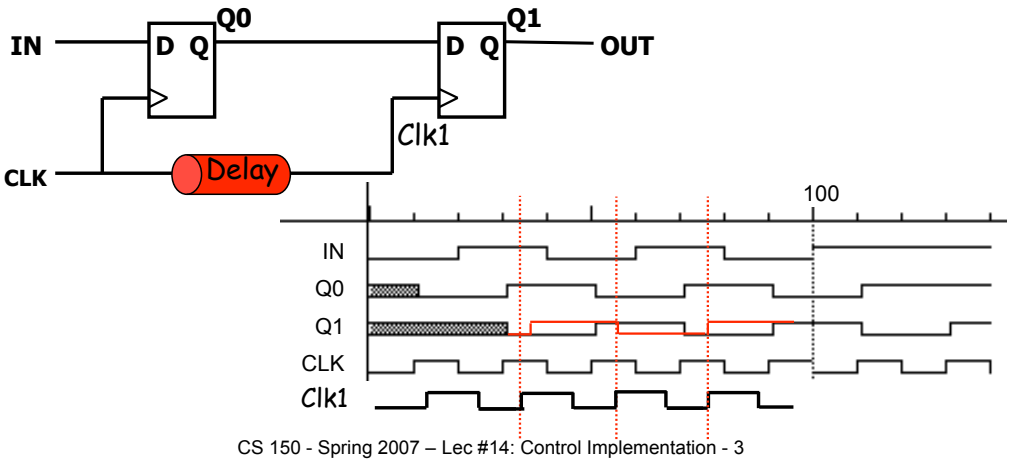
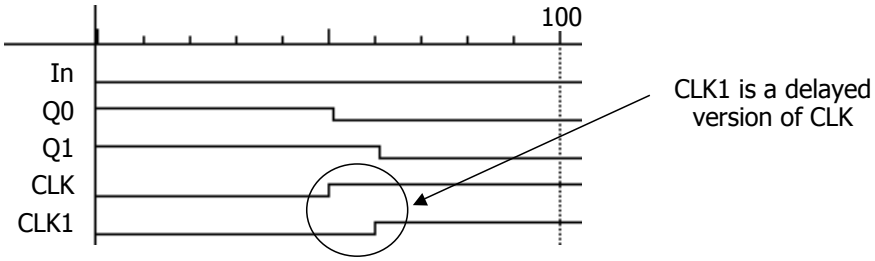


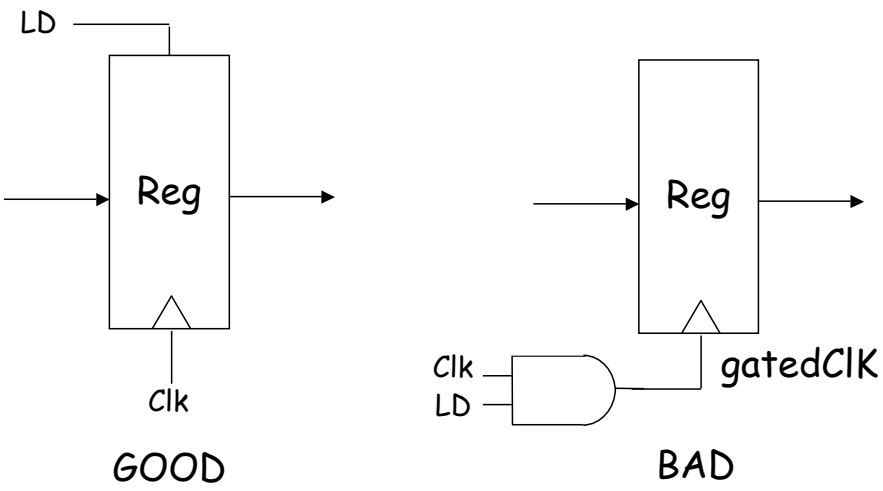
Clock Skew

- The problem
  - Correct behavior assumes next state of all storage elements determined by all storage elements at the same time
  - Difficult in high-performance systems because time for clock to arrive at flip-flop is comparable to delays through logic (and will soon become greater than logic delay)
  - Effect of skew on cascaded flip-flops:



original state: IN = 0, Q0 = 1, Q1 = 1
due to skew, next state becomes: Q0 = 0, Q1 = 0, and not Q0 = 0, Q1 = 1

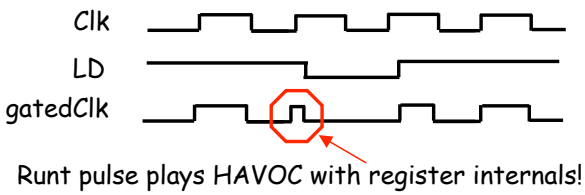
Why Gating of Clocks is Bad!



Do NOT Mess With Clock Signals!

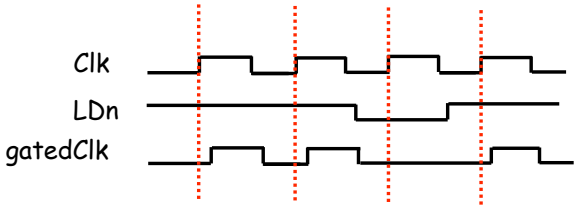
Why Gating of Clocks is Bad!

LD generated by FSM
shortly after rising edge of CLK



Runt pulse plays HAVOC with register internals!

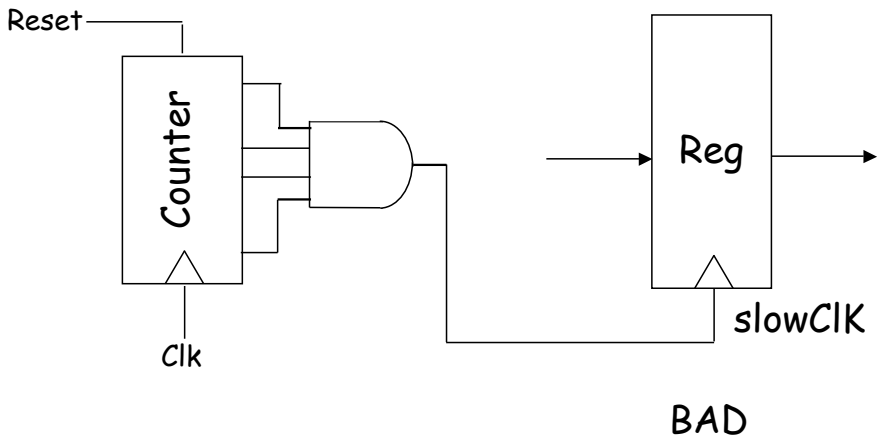
NASTY HACK: delay LD through negative edge triggered FF to ensure that it won't change during next positive edge event



Clk skew PLUS LD delayed by half clock cycle …
What is the effect on your register transfers?

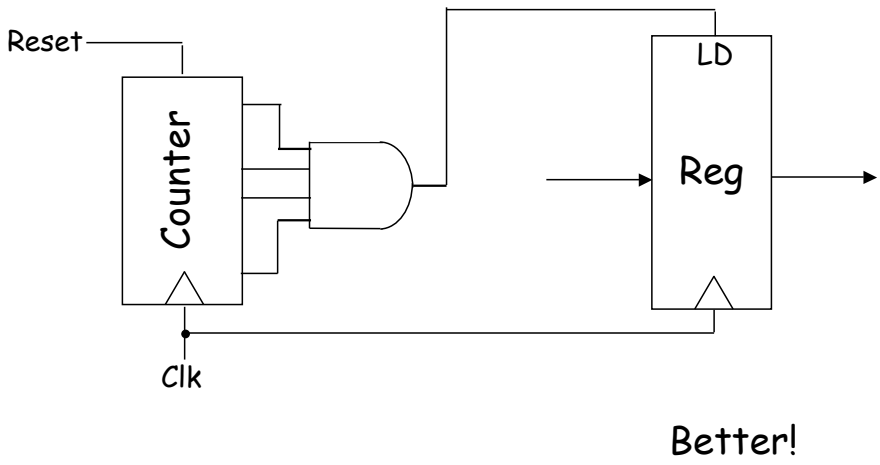
Do NOT Mess With Clock Signals!

Why Gating of Clocks is Bad!



Do NOT Mess With Clock Signals!

Why Gating of Clocks is Bad!



Do NOT Mess With Clock Signals!

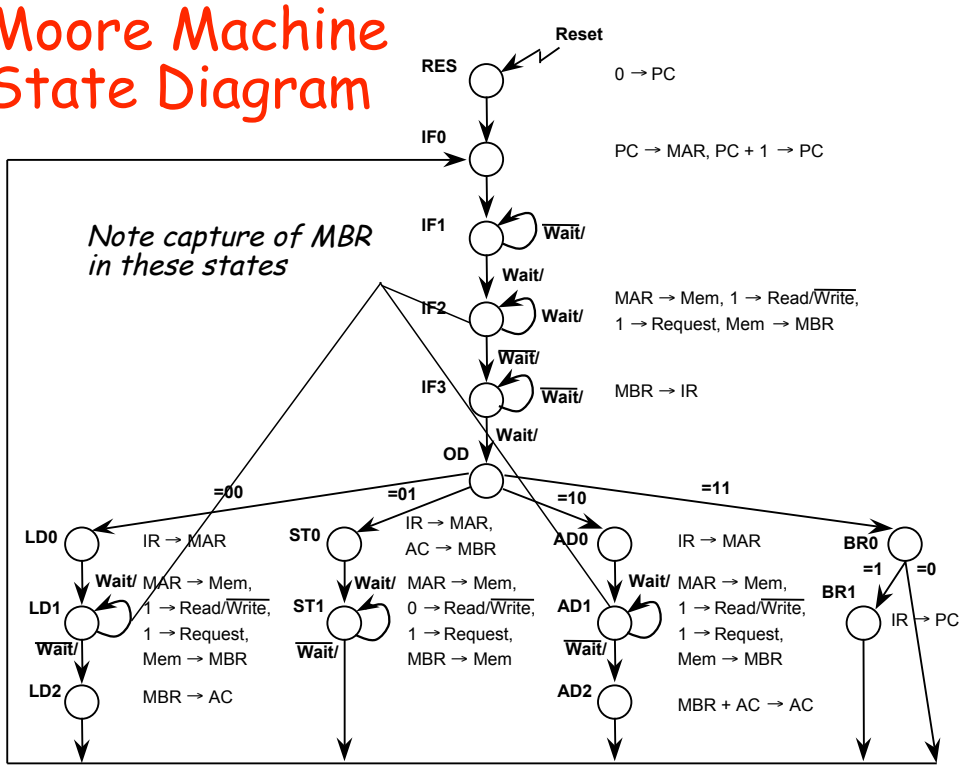
Alternative Ways to Implement Processor FSMs

- "Random Logic" based on Moore and Mealy Design
  - Classical Finite State Machine Design
- Divide and Conquer Approach: Time-State Method
  - Partition FSM into multiple communicating FSMs
- Exploit Logic Block Functionality: Jump Counters
  - Counters, Multiplexers, Decoders
- Microprogramming: ROM-based methods
  - Direct encoding of next states and outputs

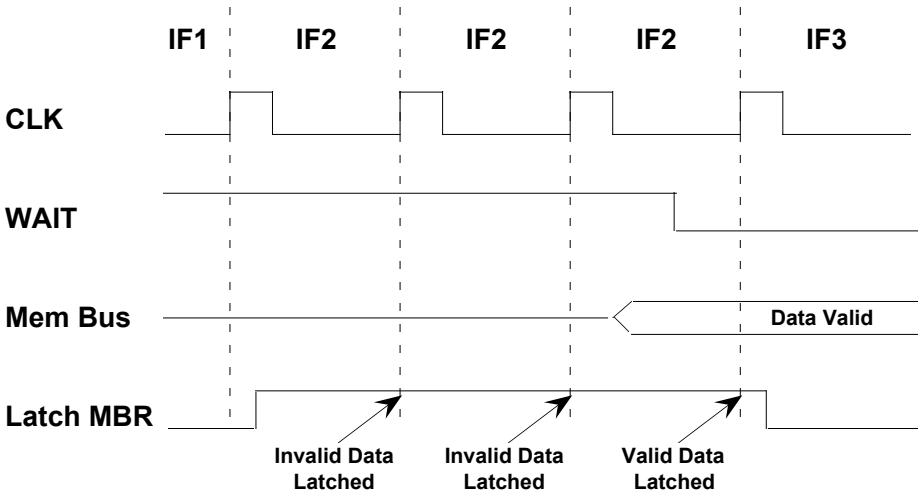
Random Logic

- Perhaps poor choice of terms for "classical" FSMs
- Contrast with structured logic: PLA, FPGA, ROM-based (latter used in microprogrammed controllers)
- Could just as easily construct Moore and Mealy machines with these components

Moore Machine State Diagram

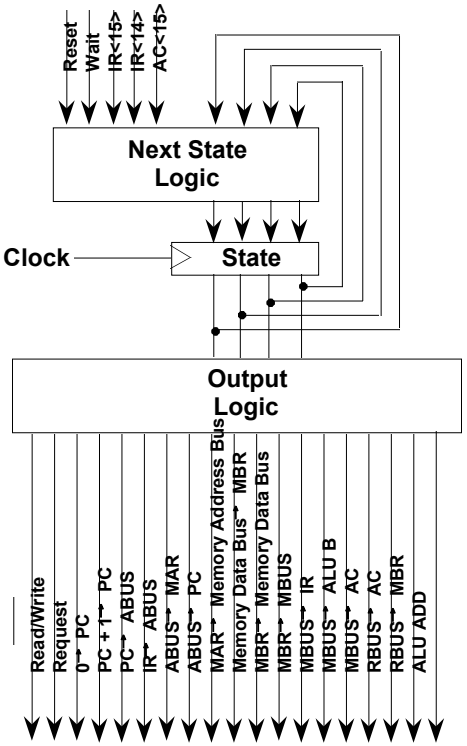


Memory-Register Interface Timing



Valid data latched on IF2 to IF3 transition because data must be valid before Wait can go low

Moore Machine Diagram



16 states, 4 bit state register

Next State Logic: 9 Inputs, 4 Outputs

Output Logic: 4 Inputs, 18 Outputs

These can be implemented via ROM or PAL/PLA

Next State: 512 x 4 bit ROM
Output: 16 x 18 bit ROM

Moore Machine State Table

Reset	Wait	IR<15>	IR<14>	AC<15>	Current State	Next State	Register Transfer Ops
1	X	X	X	X	X	RES (0000)	
0	X	X	X	X	RES (0000)	IF0 (0001)	0 → PC
0	X	X	X	X	IF0 (0001)	IF1 (0001)	PC → MAR, PC + 1 → PC
0	0	X	X	X	IF1 (0010)	IF1 (0010)	
0	1	X	X	X	IF1 (0010)	IF2 (0011)	
0	1	X	X	X	IF2 (0011)	IF2 (0011)	MAR → Mem, Read,
0	0	X	X	X	IF2 (0011)	IF3 (0100)	Request, Mem → MBR
0	0	X	X	X	IF3 (0100)	IF3 (0100)	MBR → IR
0	1	X	X	X	IF3 (0100)	OD (0101)	
0	X	0	0	X	OD (0101)	LD0 (0110)	
0	X	0	1	X	OD (0101)	ST0 (1001)	
0	X	1	0	X	OD (0101)	AD0 (1011)	
0	X	1	1	X	OD (0101)	BR0 (1110)	

Moore Machine State Table

Reset	Wait	IR<15>	IR<14>	AC<15>	Current State	Next State	Register Transfer Ops
0	X	X	X	X	LD0 (0110)	LD1 (0111)	IR → MAR
0	1	X	X	X	LD1 (0111)	LD1 (0111)	MAR → Mem, Read,
0	0	X	X	X	LD1 (0111)	LD2 (1000)	Request, Mem → MBR
0	X	X	X	X	LD2 (1000)	IF0 (0001)	MBR → AC
0	X	X	X	X	ST0 (1001)	ST1 (1010)	IR → MAR, AC → MBR
0	1	X	X	X	ST1 (1010)	ST1 (1010)	MAR → Mem, Write,
0	0	X	X	X	ST1 (1010)	IF0 (0001)	Request, MBR → Mem
0	X	X	X	X	AD0 (1011)	AD1 (1100)	IR → MAR
0	1	X	X	X	AD1 (1100)	AD1 (1100)	MAR → Mem, Read,
0	0	X	X	X	AD1 (1100)	AD2 (1101)	Request, Mem → MBR
0	X	X	X	X	AD2 (1101)	IF0 (0001)	MBR + AC → AC
0	X	X	X	0	BR0 (1110)	IF0 (0001)	
0	X	X	X	1	BR0 (1110)	BR1 (1111)	
0	X	X	X	X	BR1 (1111)	IF0 (0001)	IR → PC

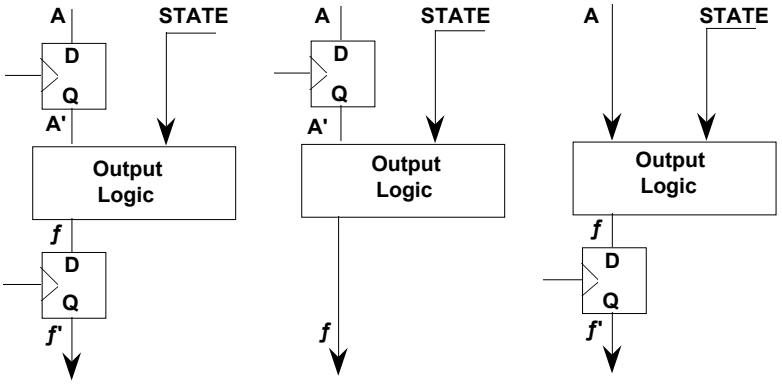
Moore Machine State Transition Table

- Observations:
  - Extensive use of Don't Cares
  - Inputs used only in a small number of state
    e.g., AC<15> examined only in BR0 state
    IR<15:14> examined only in OD state
- Some outputs always asserted in a group
- ROM-based implementations cannot take advantage of don't cares
- However, ROM-based implementation can skip state assignment step

Synchronous Mealy Machines

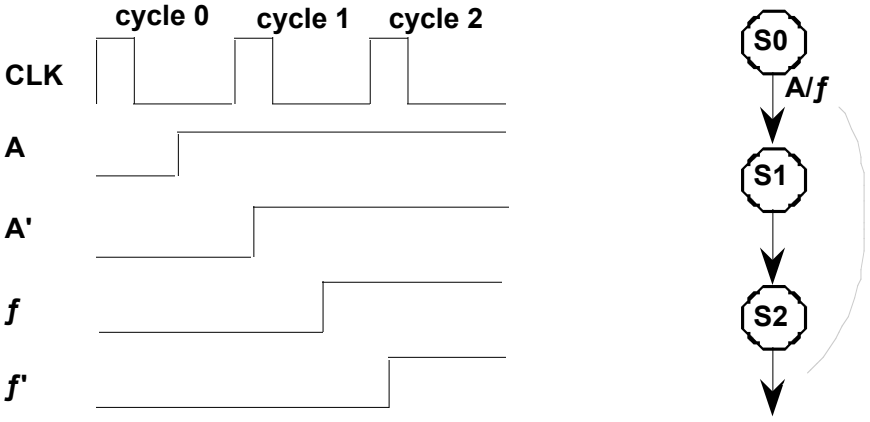
- Standard Mealy Machine has asynchronous outputs
- Change in response to input changes, independent of clock
- Revise Mealy Machine design so outputs change only on clock edges
- One approach: non-overlapping clocks

Synchronizer Circuitry at Inputs and Outputs



Synchronous Mealy Machines

Case I: Synchronizers at Inputs and Outputs

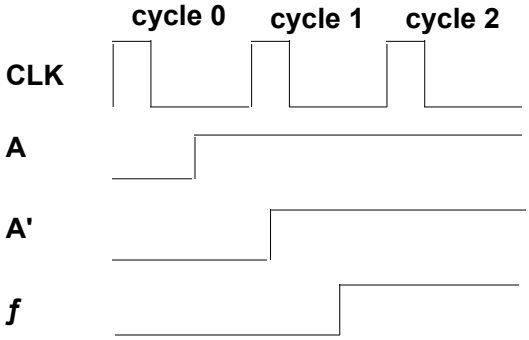


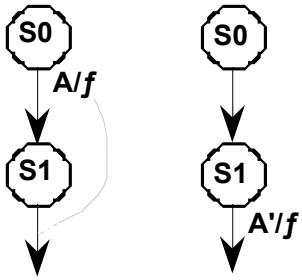
A asserted in Cycle 0, *f* becomes asserted after 2 cycle delay!

This is clearly overkill!

Synchronous Mealy Machine

Case II: Synchronizers on Inputs



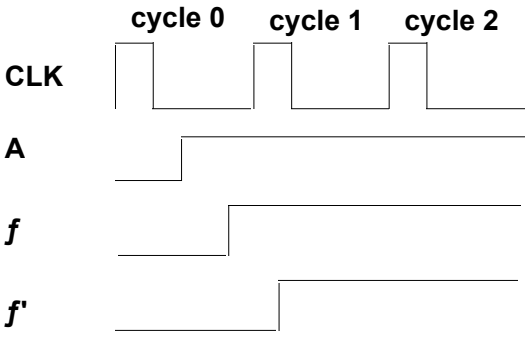


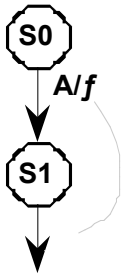
A asserted in Cycle 0, *f* follows in next cycle

Same as using delayed signal (A') in Cycle 1!

Synchronous Mealy Machines

Case III: Synchronized Outputs





A asserted during Cycle 0, *f'* asserted in next cycle

Effect of *f* delayed one cycle

Synchronous Mealy Machines

- Implications for Processor FSM Already Derived
- Consider inputs: Reset, Wait, IR<15:14>, AC<15>
  - Latter two already come from registers, and are sync'd to clock
  - Possible to load IR with new instruction in one state & perform multiway branch on opcode in next state
  - Best solution for Reset and Wait: synchronized inputs
    - » Place D flipflops between these external signals and the
    - » control inputs to the processor FSM
    - » Sync'd versions of Reset and Wait delayed by one clock cycle

Time State Divide and Conquer

- Overview
  - Classical Approach: Monolithic Implementations
  - Alternative "Divide & Conquer" Approach:
    - » Decompose FSM into several simpler communicating FSMs
    - » Time state FSM (e.g., IFetch, Decode, Execute)
    - » Instruction state FSM (e.g., LD, ST, ADD, BRN)
    - » Condition state FSM (e.g., AC < 0, AC ≠ 0)

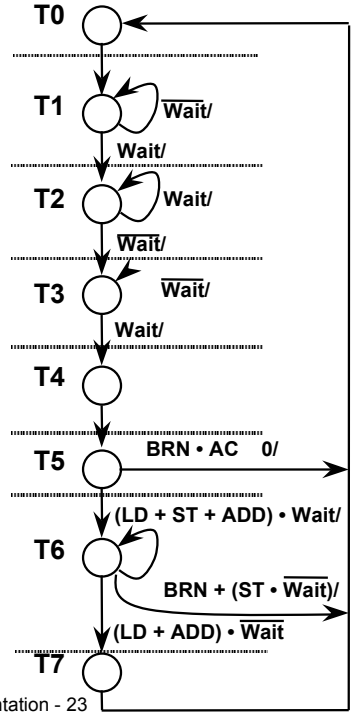
Time State (Divide & Conquer)

Time State FSM

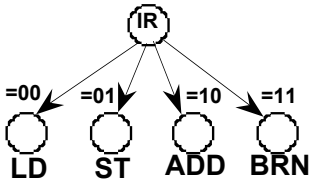
Most instructions follow same basic sequence

Differ only in detailed execution sequence

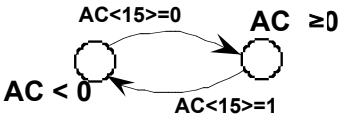
Time State FSM can be parameterized by opcode and AC states



Instruction State: stored in IR<15:14>



Condition State: stored in AC<15>



Time State (Divide & Conquer)

Generation of Microoperations

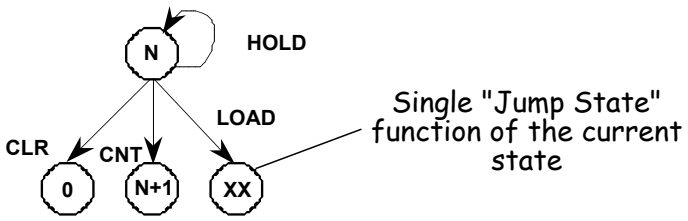
```
0 → PC: Reset
PC + 1 → PC: T0
PC → MAR: T0
MAR → Memory Address Bus: T2 + T6 · (LD + ST + ADD)
Memory Data Bus → MBR:  T2 + T6 · (LD + ADD)
MBR → Memory Data Bus:  T6 · ST
MBR → IR:  T4
MBR → AC:  T7 · LD
AC → MBR:  T5 · ST
AC + MBR → AC:  T7 · ADD
IR<13:0> → MAR:  T5 · (LD + ST + ADD)
IR<13:0> → PC:  T6 · BRN
1 → Read/Write:  T2 + T6 · (LD + ADD)
0 → Read/Write:  T6 · ST
1 → Request:  T2 + T6 · (LD + ST + ADD)
```

Jump Counter

Concept

Implement FSM using MSI functionality: counters, mux, decoders

Pure jump counter: only one of four possible next states

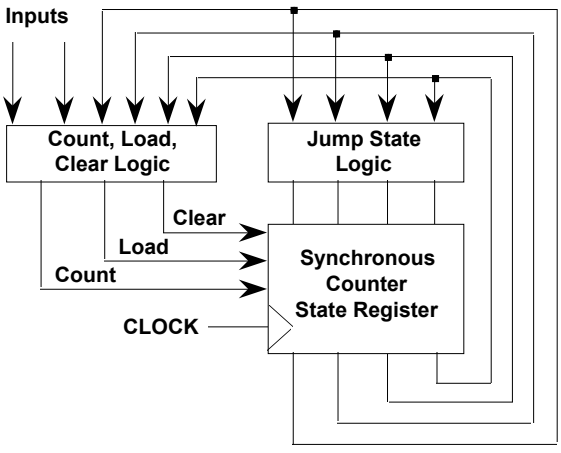


Hybrid jump counter:

Multiple "Jump States" — function of current state + inputs

Jump Counters

Pure Jump Counter



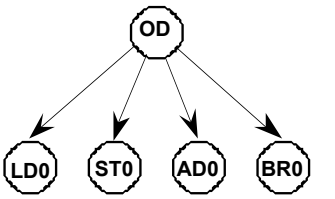
NOTE: No inputs to jump state logic

Logic blocks implemented via discrete logic, PLAs, ROMs

Jump Counters

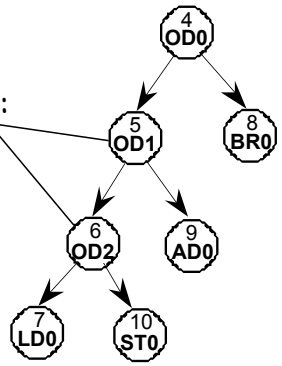
Problem with Pure Jump Counter

Difficult to implement multi-way branches



Logical State Diagram

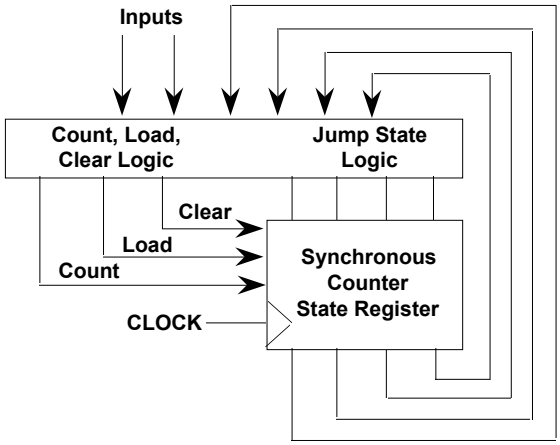
Extra States:



Pure Jump Counter State Diagram

Jump Counters

Hybrid Jump Counter

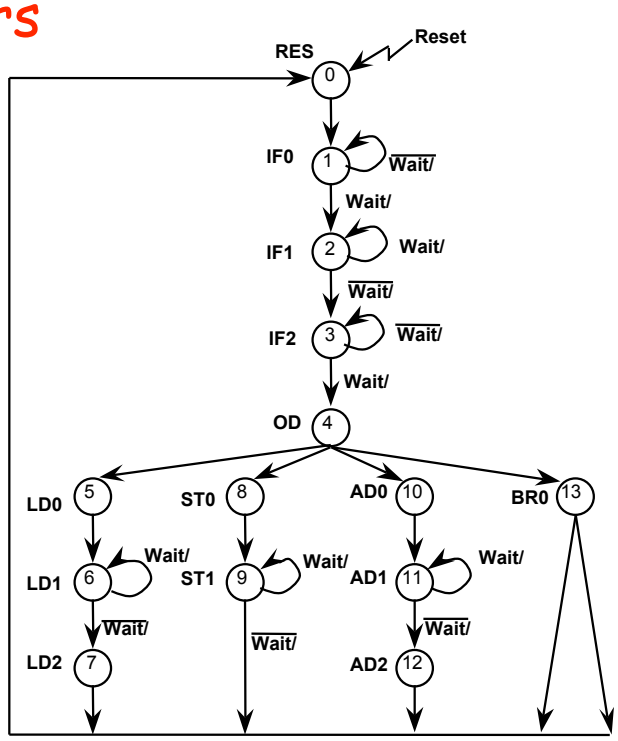


Load inputs are function of state and FSM inputs

Jump Counters

Implementation Example

State assignment attempts to take advantage of sequential states



Jump Counters

Implementation Example, Continued

$$CNT = (s0 + s5 + s8 + s10) + Wait \cdot (s1 + s3) + \overline{Wait} \cdot (s2 + s6 + s9 + s11)$$

$$\overline{CNT} = \overline{Wait} \cdot (s1 + s3) + Wait \cdot (s2 + s6 + s9 + s11)$$

$$CLR = Reset + s7 + s12 + s13 + (s9 \cdot \overline{Wait})$$

$$\overline{CLR} = \overline{Reset} \cdot \overline{s7} \cdot \overline{s12} \cdot \overline{s13} \cdot (\overline{s9} + Wait)$$

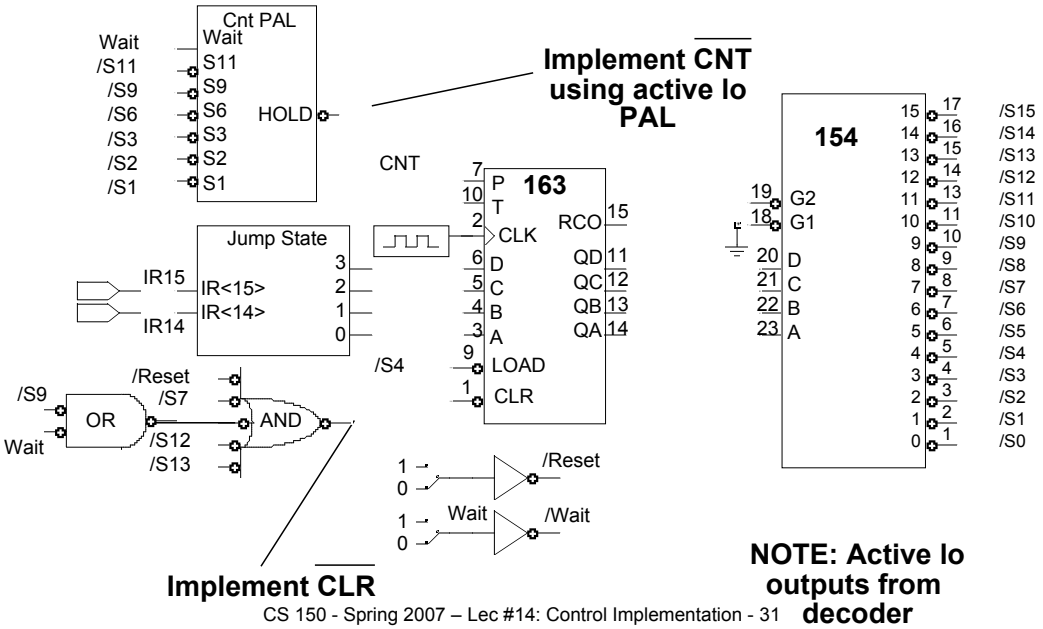
$$LD = s4$$

Contents of Jump State ROM

Address	*Contents (Symbolic State)*
00	0101 (LD0)
01	1000 (ST0)
10	1010 (AD0)
11	1101 (BR0)

Jump Counters

Implementation Example, continued



Jump Counters

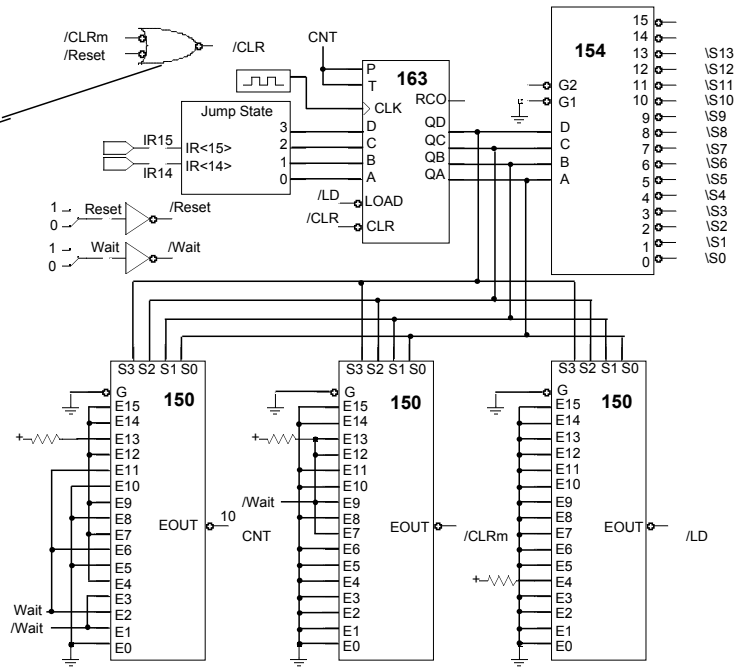
CLR, CNT, LD implemented via Mux Logic

$CLR = CLRm + Reset$

$\overline{CLR} = \overline{CLRm + Reset}$

Active Lo outputs: **hi input inverted at the output**

Note that CNT is active hi on counter so invert MUX inputs!



Jump Counters

Microoperation implementation

0 → PC = Reset
PC + 1 → PC = S0
PC → MAR = S0
MAR → Memory Address Bus =
 Wait•(S1 + S2 + S5 + S6 + S8 + S9 + S11 + S12)
Memory Data Bus → MBR = Wait•(S2 + S6 + S11)
MBR → Memory Data Bus = Wait•(S8 + S9)
MBR → IR = Wait•S3
MBR → AC = Wait•S7
AC → MBR = IR15•IR14•S4
AC + MBR → AC = Wait•S12
IR<13:0> → MAR = (IR15•IR14 + IR15•IR14 + IR15•IR14)•S4
IR<13:0> → PC = AC15•S13
1 → Read/Write = Wait•(S1 + S2 + S5 + S6 + S11 + S12)
0 → Read/Write = Wait•(S8 + S9)
1 → Request = Wait•(S1 + S2 + S5 + S6 + S8 + S9 + S11 + S12)

Jump Counters: CNT, CLR, LD function of current state + Wait
Why not store these as outputs of the Jump State ROM?
Make Wait and Current State part of ROM address
32 x as many words, 7 bits wide

Controller Implementation Summary (Part I!)

- Control Unit Organization
  - *Register transfer operation*
  - *Classical Moore and Mealy machines*
  - *Time State Approach*
  - *Jump Counter*
  - Next Time:
    - » Branch Sequencers
    - » Horizontal and Vertical Microprogramming