

(*) Building an 8-bit Breadboard Computer

by Ben Eater

(<https://youtube.com/playlist?list=PLowKtXNTBypGqImE405J2565dvjafg1HU>)

^ NOR-Gate SR Latch

(<https://youtu.be/KM0DdEaY5sY>)

Let the initial STABLE state be $S = 0$, $R = 0$, $Q = 0$ and $Q' = 1$ (CLEAR).



Let the PROPAGATION delays of the upper and lower NOR gates be 2 units and 3 units, respectively.

So, the EFFECTS of the changed inputs will be visible only AFTER the propagation delays.

In order to draw the TIMING diagrams, for every logic gate, look at its inputs at time $(t - T)$, where T is its propagation delay.

For eg., if the propagation delay of a logic gate is 3 units, then its OUTPUT at $t = 3.5$ units (say) depends upon its INPUTS at $t = 0.5$ units.

Now, let S get changed to 1 at $t = 0$ (in order for the latch to become SET).

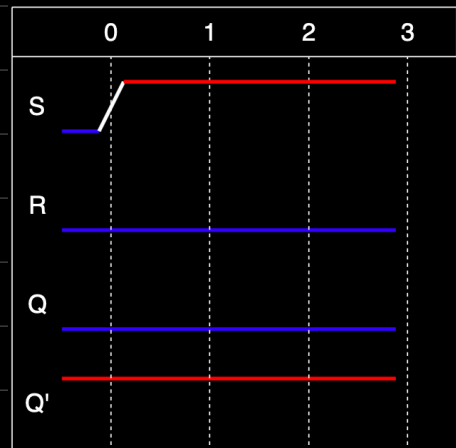
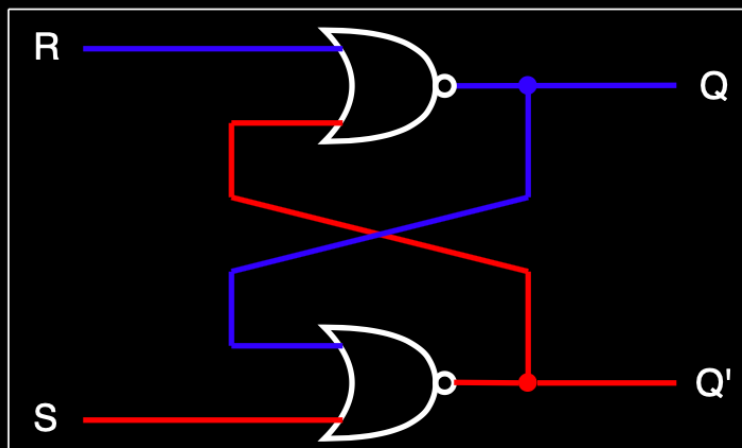
From $t = 0$ to $t = 1$:-



From $t = 1$ to $t = 2$:-



From $t = 2$ to $t = 3$:-



From $t = 3$ to $t = 4$:-



From $t = 4$ to $t = 5$:-



From $t = 5$ to $t = 6$:-



Now, the latch will stay STABLE in the SET state, even if S gets changed back to 0.

Let S get changed back to 0 at $t = 6$.

From $t = 6$ to $t = 7$:-



From $t = 7$ to $t = 8$:-



Hence, the latch will stay STABLE in the SET state, as long as S was maintained at 1 for a LONG ENOUGH time, i.e. if S gets changed back to 0 AFTER $t = 5$, then the latch will result in a STABLE SET state.

Now, let S get changed back to 0 at $t = 4$, instead of at $t = 6$.

From $t = 4$ to $t = 5$:-



From $t = 5$ to $t = 6$:-



From $t = 6$ to $t = 7$:-



From $t = 7$ to $t = 8$:-



From $t = 8$ to $t = 9$:-



From $t = 9$ to $t = 10$:-



From $t = 10$ to $t = 11$:-



From $t = 11$ to $t = 12$:-



From $t = 12$ to $t = 13$:-



The latch will keep oscillating like this FOREVER. Previously, when the latch was being SET, it temporarily switched to an INVALID state, i.e. $Q = Q' = 0$, but then it became STABLE in the SET state. But, in this case, the latch will NEVER become STABLE in ANY state. Therefore, if S is NOT maintained at 1 for a LONG ENOUGH time, then problems like this may occur.

It should be noted that the above analysis corresponds to an IDEAL version of logic gates. In real-world circuits, for EDGE cases like this, logic gates may NOT work as expected. For eg., even though ideally the latch should keep oscillating FOREVER, in real-world circuits, the latch MAY or MAY NOT keep oscillating due to the time it takes to turn on and off transistors, to charge internal capacitors, etc. In real-world circuits, a change in the inputs for a SMALL enough time does NOT contain enough ENERGY to cause a logic gate to switch its output.

In any case, if used CORRECTLY, i.e. by keeping S/R high for a LONG ENOUGH time when setting/clearing the latch and by NOT keeping S & R high at the same time, then the latch will work AS EXPECTED in ideal as well as real-world circuits.

Now, Let the initial STABLE state be $S = 0$, $R = 0$, $Q = 1$ and $Q' = 0$ (SET).



Let R get changed to 1 at $t = 0$ (in order for the latch to become CLEAR).

From $t = 0$ to $t = 1$:-



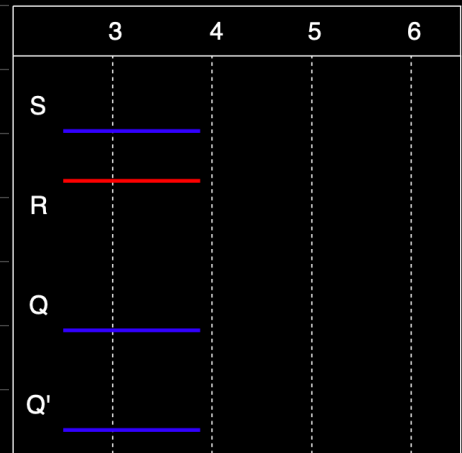
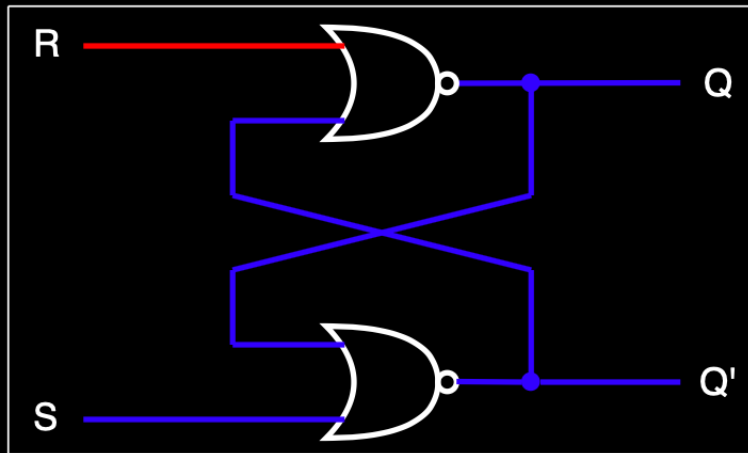
From $t = 1$ to $t = 2$:-



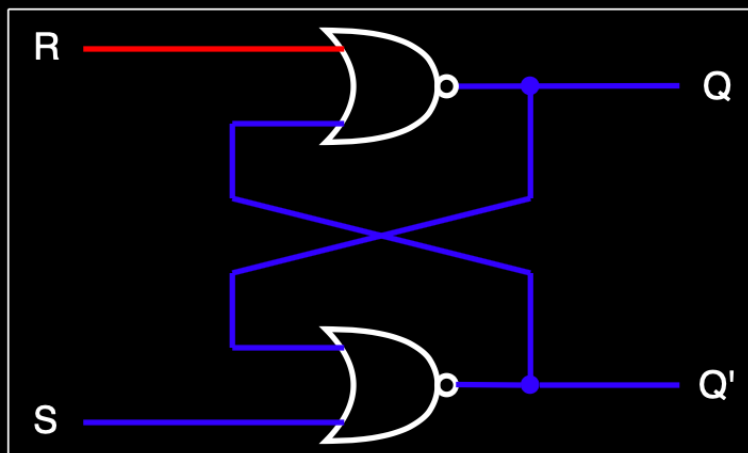
From $t = 2$ to $t = 3$:-



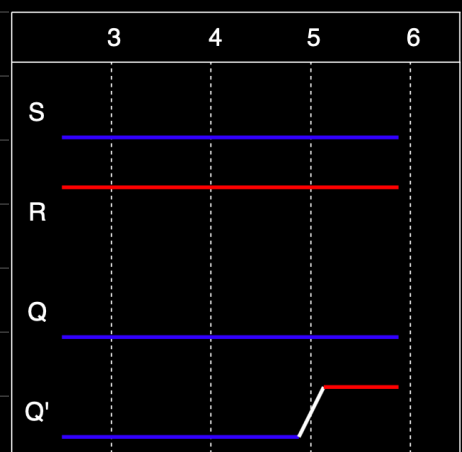
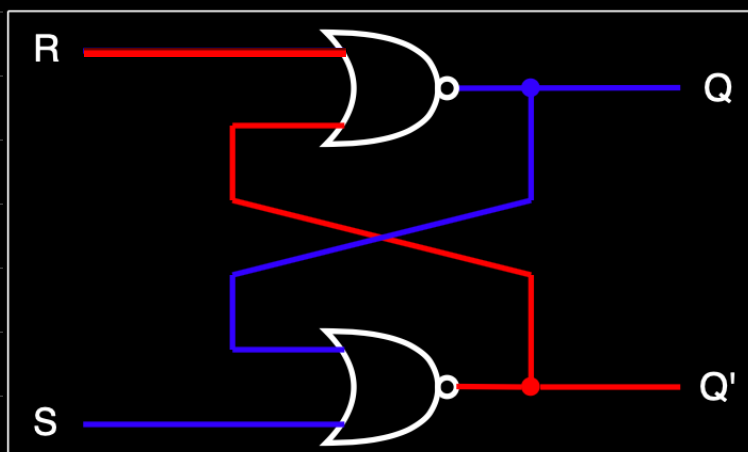
From $t = 3$ to $t = 4$:-



From $t = 4$ to $t = 5$:-



From $t = 5$ to $t = 6$:-



Now, the latch will stay STABLE in the CLEAR state, even if R gets changed back to 0, as long as R was maintained at 1 for a LONG ENOUGH time, i.e. if R gets changed back to 0 AFTER $t = 5$, then the latch will result in a STABLE CLEAR state.

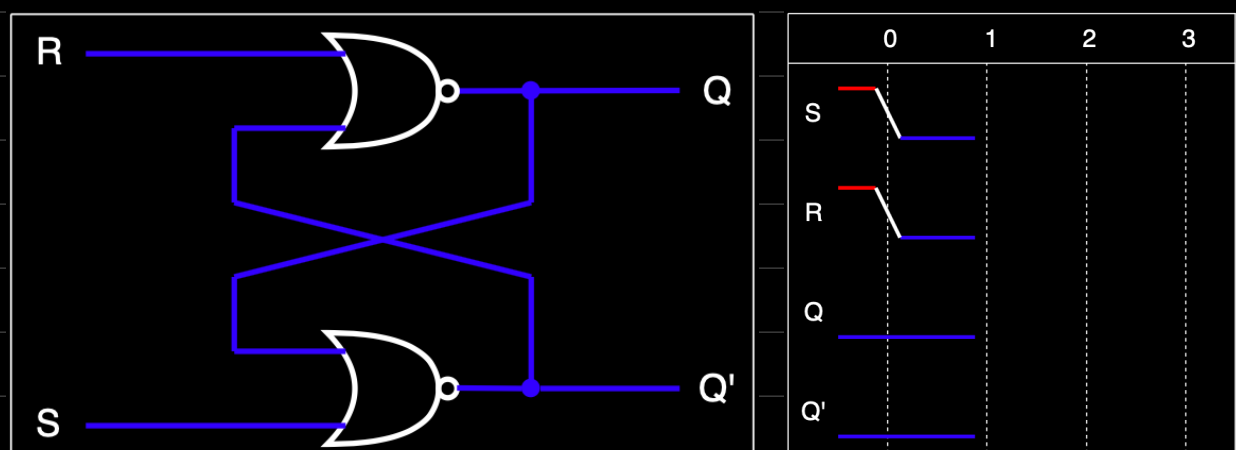
Therefore, if R is NOT maintained at 1 for a LONG ENOUGH time, then similar problems may occur like if S is NOT maintained at 1 for a LONG ENOUGH time when SETTING the latch.

Now, Let the initial STABLE state be $S = 1$, $R = 1$, $Q = 0$ and $Q' = 0$ (INVALID).



Let S & R both get changed to 0 at $t = 0$.

From $t = 0$ to $t = 1$:-



From $t = 1$ to $t = 2$:-



From $t = 2$ to $t = 3$:-



From $t = 3$ to $t = 4$:-



From $t = 4$ to $t = 5$:-



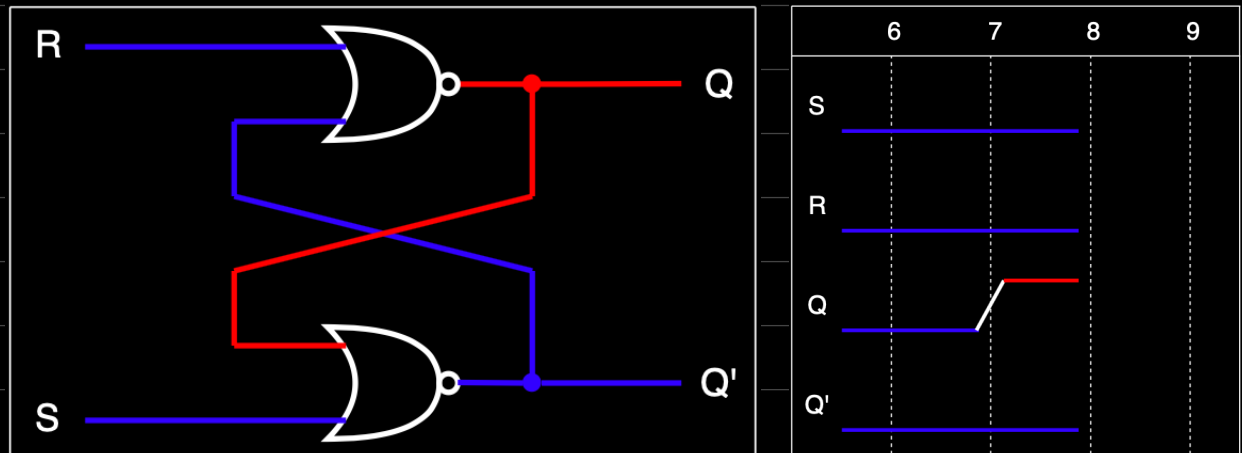
From $t = 5$ to $t = 6$:-



From $t = 6$ to $t = 7$:-



From $t = 7$ to $t = 8$:-



The latch will keep oscillating like this FOREVER.

Therefore, if S and R both get changed to 0 after the latch is STABLE in the INVALID state of $S = 1, R = 1, Q = 0$ and $Q' = 0$, then problems like this may occur.

As stated previously, in real-world circuits, the latch MAY or MAY NOT keep oscillating.

In any case, the state of $S = 1, R = 1, Q = 0$ and $Q' = 0$ should be AVOIDED in ideal as well as real-world circuits.

It should be noted that if the initial STABLE state is $S = 0, R = 0, Q = 1$ and $Q' = 0$ (SET), and if S gets changed to 1, then the latch will REMAIN in the SET state.

Similarly, if the initial STABLE state is $S = 0, R = 0, Q = 0$ and $Q' = 1$ (CLEAR), and if R gets changed to 1, then the latch will REMAIN in the CLEAR state.

It should be noted that, for eg., while setting/clearing the latch, S/R was PURPOSEFULLY not changed back to 0 EXACTLY at $t = 5$ because doing so may work IDEALLY, but MAY or MAY NOT work in REAL-WORLD circuits.

To be answered later (?) :-

After a stable state of $S = 0$, $R = 0$, $Q = 1/0$ and $Q' = 0/1$, if S & R both get changed to 1 and then back to 0 without waiting for a long enough time, then what happens?

After a stable state of $S = 1/0$, $R = 0/1$, $Q = 1/0$ and $Q' = 0/1$, if R/S gets changed to 1 and then after waiting for a long enough time or without waiting for a long enough time, S/R gets changed to 0 and stays at 0 for a long enough time, then what happens?
– The latch goes into a stable clear/set state.

This is because after S and R become constant at $1/0$ and $0/1$ (including floating at $1/0$ and $0/1$), respectively, then no matter the current state of the latch, stable, oscillating between 0 & 1, or even floating (at 0, 1 or somewhere between 0 & 1, or oscillating among 0, 1 and somewhere between 0 & 1), the latch will result in a stable set/clear state after a long enough time.

For eg., if one input of a NOR gate becomes 1 (including floating at 1), then after its propagation delay, its output will become 0 irrespective of the other input (even if that other input is floating (at 0, 1 or somewhere between 0 & 1, or oscillating among 0, 1 and somewhere between 0 & 1)).

After a stable state of $S = 1$, $R = 1$, $Q = 0$ and $Q' = 0$, if only S/R gets changed to 0, then what happens? – The latch goes into a stable clear/set state.

But, if the other input gets changed to 0 as well without waiting for a long enough time for the latch to go into a stable clear/set state, then what happens?

Etc.

^

NOR-Gate Gated D Latch

(https://youtu.be/peCh_859q7Q?si=M2RUMPA18BvUnTm)

To be answered later (?) :-

When the enable/clock is high and the latch is stable, then after changing D and keeping it constant for a long enough time, why does the NOT gate's propagation delay not cause problems?

The answer to this question is similar to the answer to the following question for the NOR-gate SR latch -

After a stable state of $S = 1/0$, $R = 0/1$, $Q = 1/0$ and $Q' = 0/1$, if R/S gets changed to 1 and then after waiting for a long enough time or without waiting for a long enough time, S/R gets changed to 0 and stays at 0 for a long enough time, then what happens? - The latch goes into a stable clear/set state.

This is because after S and R become constant at $1/0$ and $0/1$ (including floating at $1/0$ and $0/1$), respectively, then no matter the current state of the latch, stable, oscillating between 0 & 1, or even floating (at 0, 1 or somewhere between 0 & 1, or oscillating among 0, 1 and somewhere between 0 & 1), the latch will result in a stable set/clear state after a long enough time.

For eg., if one input of a NOR gate becomes 1 (including floating at 1), then after its propagation delay, its output will become 0 irrespective of the other input (even if that other input is floating (at 0, 1 or somewhere between 0 & 1, or oscillating among 0, 1 and somewhere between 0 & 1)).

Etc.

^	NAND-Gate Truly Positive Edge-Triggered D Flip-Flop (https://youtu.be/YW-_GkUguMM)
	Ben uses the RESISTOR-CAPACITOR method for EDGE-TRIGGERING. However, the D flip-flops of the ICs that he later uses for the REGISTERS are based on the undermentioned method for EDGE-TRIGGERING.
	Let the PROPAGATION delay of every NAND gate be 1 unit, and the DURATION of a CLOCK CYCLE be 20 units, with the clock staying at HIGH & LOW for 10 units each and the clock transitioning from LOW to HIGH at $t = 20 T$, where T is an integer.
	In real-world circuits, the duration of a clock cycle is MUCH MORE than this.
	The SETUP time (i.e. the DURATION for which D must be CONSTANT while CP is at 0 IMMEDIATELY BEFORE CP gets changed from 0 to 1) is 2 units. The HOLD time (i.e. the DURATION for which D must be CONSTANT while CP is at 1 IMMEDIATELY AFTER CP gets changed from 0 to 1) is 1 unit. Hence, D must be constant from $t = (20 T - 2)$ to $t = (20 T + 1)$. [These SETUP and HOLD times were calculated AFTER understanding the undermentioned transitions]
	Let the initial STABLE state be $CP = 0$, $D = 0$, $Q = 0$ and $Q' = 1$ (CLEAR), and let the NEXT bit to be stored be 0 (which is present at the D input at $t = 0$ and whose SETUP time is completed), then 1, then 1, and then 0.
	Let the next bit to be stored arrive at the D input WHILE the clock is STILL at 1 such that the HOLD time constraint is not violated, say at $t = (20 T + 7)$.

Till $t = 0$:-

From $t = 0$ to $t = 1$:-

From $t = 1$ to $t = 7$:-



From $t = 7$ to $t = 10$:-

From $t = 10$ to $t = 11$:-

From $t = 11$ to $t = 12$:-



From $t = 12$ to $t = 13$:-

From $t = 13$ to $t = 20$:-

From $t = 20$ to $t = 21$:-



From t = 21 to t = 22 :-



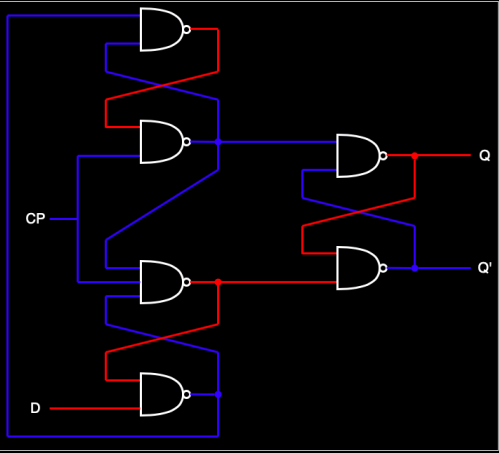
From t = 22 to t = 23 :-



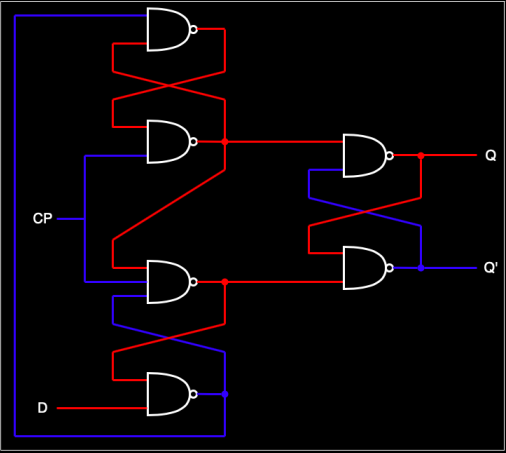
From t = 23 to t = 30 :-



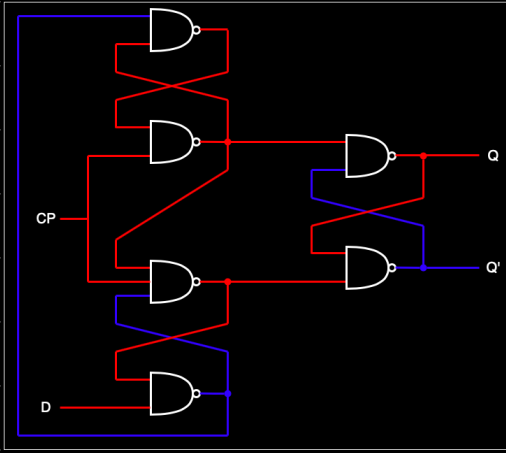
From t = 30 to t = 31 :-



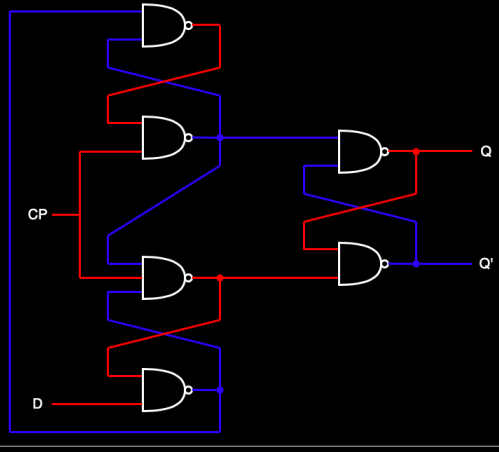
From t = 31 to t = 40 :-



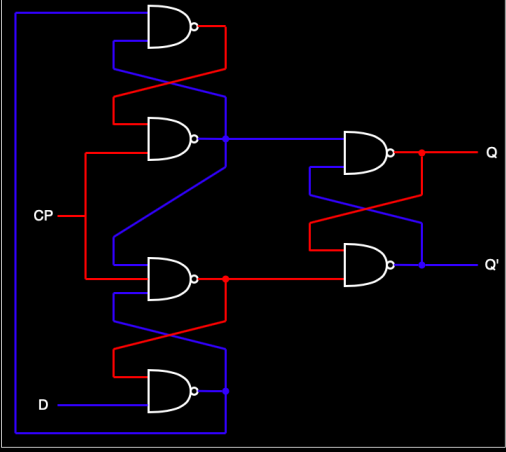
From t = 40 to t = 41 :-



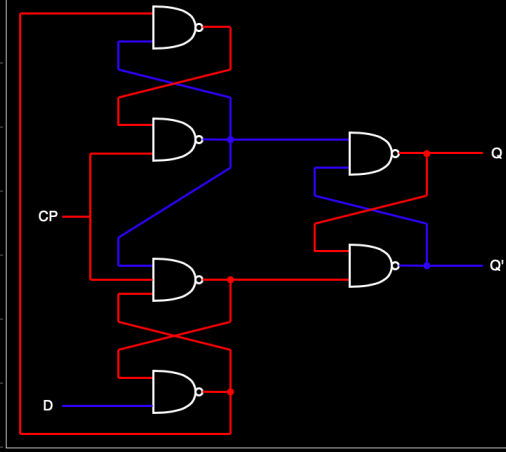
From t = 41 to t = 47 :-



From t = 47 to t = 48 :-



From t = 48 to t = 50 :-



From t = 50 to t = 51 :-



From t = 51 to t = 52 :-



From t = 52 to t = 60 :-



From t = 60 to t = 61 :-



From t = 61 to t = 62 :-



From t = 62 to t = 63 :-



From t = 63 onwards :-



Explanation for the SETUP time and the HOLD time when the flip-flop is getting changed from CLEAR to SET :-

Let the initial STABLE state be
 $CP = 0$, $D = 0$, $Q = 0$ and
 $Q' = 1$ (CLEAR).

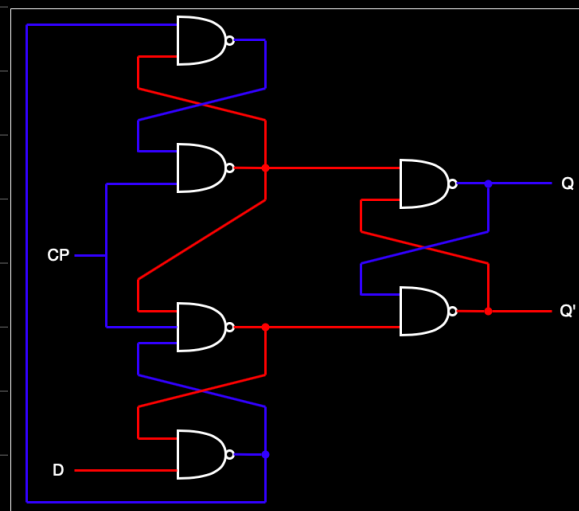
Let D get changed to 1 at $t = 0$.



From $t = 0$ to $t = 1$ -



From $t = 1$ to $t = 2$ -



From $t = 2$ onwards -

So, the SETUP time is equal to the propagation delays through the BOTTOMMOST gate and then through the TOPMOST gate.



Now, let the initial STABLE state be $CP = 0$, $D = 1$, $Q = 0$ and $Q' = 1$ (CLEAR) and let CP get changed to 1 at $t = 0$.

From $t = 0$ to $t = 1$ -



From $t = 1$ to $t = 2$ -

So, changing D AFTER $t = 1$ will NOT affect the latch's next state, even if the propagation delays through the BOTTOMMOST gate and then through the TOPMOST gate are NEGLIGIBLE.



Therefore, the HOLD time is equal to the propagation delay through the UPPER gate to which CP is connected.

Explanation for the SETUP time and the HOLD time when the flip-flop is getting changed from SET to CLEAR :-

Let the initial STABLE state be
 $CP = 0$, $D = 1$, $Q = 1$ and
 $Q' = 0$ (SET).

Let D get changed to 0 at $t = 0$.



From $t = 0$ to $t = 1$ -



From $t = 1$ to $t = 2$ -



From $t = 2$ onwards -

So, the SETUP time is equal to the propagation delays through the BOTTOMMOST gate and then through the TOPMOST gate. In the aforementioned transitions, from $t = 50$ onwards, it may SEEM like



the SETUP time is 1 unit, but it should be noted that the FIRST part of SETUP, i.e. the propagation through the BOTTOMMOST gate, was already completed when CP was high.

Now, let the initial STABLE state be $CP = 0$, $D = 0$, $Q = 1$ and $Q' = 0$ (SET) and let CP get changed to 1 at $t = 0$.

From $t = 0$ to $t = 1$ -



From $t = 1$ to $t = 2$ -

So, changing D AFTER $t = 1$ will NOT affect the latch's next state, even if the propagation delay through the BOTTOMMOST gate is NEGLIGIBLE. Therefore, the HOLD time is equal to the



propagation delay through the LOWER gate to which CP is connected.

In the computer to be developed in Ben Eater's playlist, and in GENERAL, the data to be loaded into truly POSITIVE edge-triggered flip-flops in the NEXT clock cycle arrive at the inputs while the clock is LOW, while the clock was previously HIGH, etc., such that the SETUP time constraint is NOT violated.

Then, the data get loaded into those AFTER the clock goes HIGH in the NEXT clock cycle.

Finally, the inputs may get changed while the clock is still HIGH, after the clock goes LOW, etc., such that the HOLD time constraint is NOT violated.

These changed inputs MAY or MAY NOT correspond to the data to be loaded in the future. [Similarly for truly NEGATIVE edge-triggered flip-flops]

To be answered later (?) :-

What happens if D is not maintained constant during the setup time?

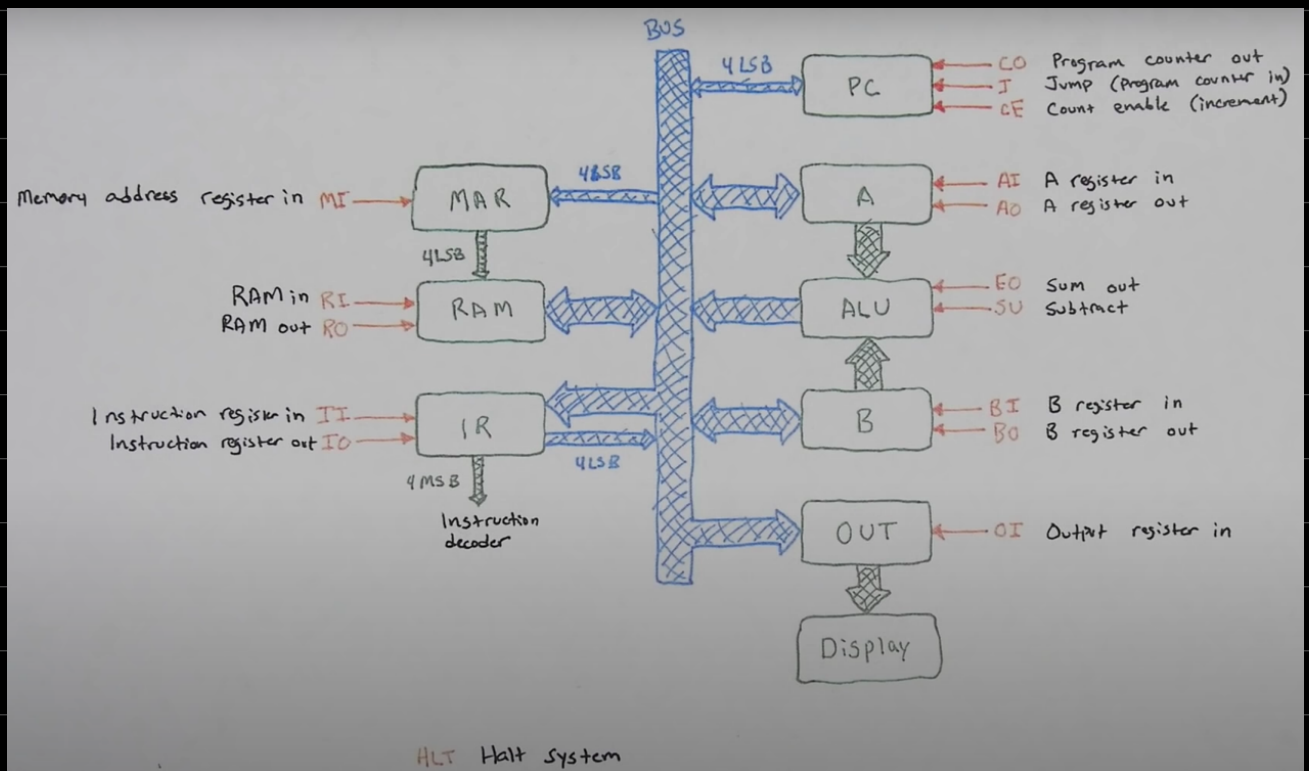
What happens if CP gets changed to 1 before the setup time is completed?

What happens if D is not maintained constant for the hold time?

What happens if CP is not maintained at 1 for a long enough time?

Etc.

Overview



There are a total of 16 control signals, forming 16-bit CONTROL WORDS.

From the above diagram, BO (B Register Out) is not used, and is ALWAYS disabled.

Instead of BO, FI (Flags Register In) is used.

For TTL ICs (such as the 74LS series), those INPUTS which are FLOATING (at 0, 1 or somewhere between 0 & 1, or oscillating among 0, 1 and somewhere between 0 & 1) (for eg., due to being DISCONNECTED, due to those OUTPUTS which are driving these INPUTS FLOATING (at 0, 1 or somewhere between 0 & 1, or oscillating among 0, 1 and somewhere between 0 & 1), etc.) IDEALLY get converted to 1's.

But, in REAL-WORLD circuits, such inputs are EXTREMELY sensitive to various factors such as the EXTERNAL electrical NOISE, etc.

So, in REAL-WORLD circuits, such inputs remain FLOATING (at 0, 1 or somewhere between 0 & 1, or oscillating among 0, 1 and somewhere between 0 & 1).

For eg., if ONE input of an OR gate becomes 1 (including FLOATING at 1), then after its PROPAGATION delay, its OUTPUT will become 0 IRRESPECTIVE of the OTHER input (even if that OTHER input is FLOATING (at 0, 1 or somewhere between 0 & 1, or oscillating among 0, 1 and somewhere between 0 & 1)).

However, if ONE input of an OR gate becomes 0 (including FLOATING at 0) and the OTHER input becomes FLOATING somewhere between 0 & 1, or if BOTH inputs become FLOATING somewhere between 0 & 1, then after its PROPAGATION delay, its OUTPUT will become FLOATING (at 0, 1 or somewhere between 0 & 1, or oscillating among 0, 1 and somewhere between 0 & 1) if its OUTPUT is NOT being driven by some other component.

If the ENABLE input of a tri-state buffer is 0 (including FLOATING at 0) or FLOATING somewhere between 0 & 1, then the tri-state buffer is said to be DISABLED, whereas if the ENABLE input of a tri-state buffer is 1 (including FLOATING at 1), then the tri-state buffer is said to be ENABLED.

If a tri-state buffer becomes DISABLED, then after its PROPAGATION delay, its OUTPUT will become FLOATING (at 0, 1 or somewhere between 0 & 1, or oscillating among 0, 1 and somewhere between 0 & 1) if its OUTPUT is NOT being driven by some other component.

Moreover, SIMILAR to the aforementioned example of an OR gate, if a tri-state buffer is ENABLED, but its input becomes FLOATING somewhere between 0 & 1, then after its PROPAGATION delay, its OUTPUT will become FLOATING (at 0, 1 or somewhere between 0 & 1, or oscillating among 0, 1 and somewhere between 0 & 1) if its OUTPUT is NOT being driven by some other component.

If the input of ONE tri-state buffer which is ENABLED and whose OUTPUT is connected to a BUS wire becomes 0/1 (including FLOATING at 0/1), then after its PROPAGATION delay, the value on that BUS wire will become 0/1, provided that ALL OTHER tri-state buffers whose OUTPUTS are connected to that BUS wire are either DISABLED, or ENABLED with their INPUTS FLOATING somewhere between 0 & 1.

The BUS is constructed such that the values on its wires become 0's when the BUS is NOT being driven. So, if ALL tri-state buffers whose OUTPUTS are connected to a BUS wire are either DISABLED, or ENABLED with their INPUTS FLOATING somewhere between 0 & 1, then the value on that BUS wire will become 0.

However, for the MOST part, there would be NO problems of ARBITRARY values getting loaded into GATED LATCHES / FLIP-FLOPS EVEN IF the values on the BUS wires would be FLOATING (at 0, 1 or somewhere between 0 & 1, or oscillating among 0, 1 and somewhere between 0 & 1) when the BUS is NOT being driven.

This is because for EVERY component, the CLOCK input being 0, the CLOCK input being 1 but its POSITIVE edge-transition having gone by, or the IN signal being 0 would determine the OUTPUT(s) of the corresponding logic gate(s) IRRESPECTIVE of the input(s) coming from the BUS (even FLOATING (at 0, 1 or somewhere between 0 & 1, or oscillating among 0, 1 and somewhere between 0 & 1)).

IMMEDIATELY AFTER the computer is powered up, while the initial PROPAGATIONS have NOT completed, the values on MOST of the wires (except for those which are DIRECTLY fixed to 0's/1's) will be FLOATING (at 0, 1 or somewhere between 0 & 1, or oscillating among 0, 1 and somewhere between 0 & 1), including the CLOCK inputs and the IN signals. However, the values on the BUS wires FLOATING (at 0, 1 or somewhere between 0 & 1, or oscillating among 0, 1 and somewhere between 0 & 1) when the BUS is NOT being driven WILL NOT cause problems in THIS situation as well, as the initial PROPAGATIONS will get completed only a VERY SHORT while AFTER the computer is powered up.

^ Clock



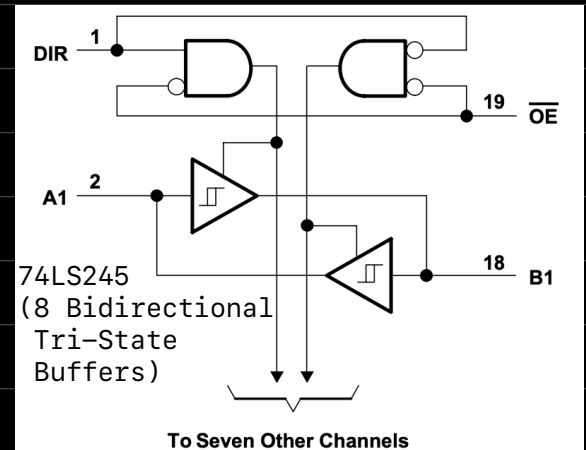
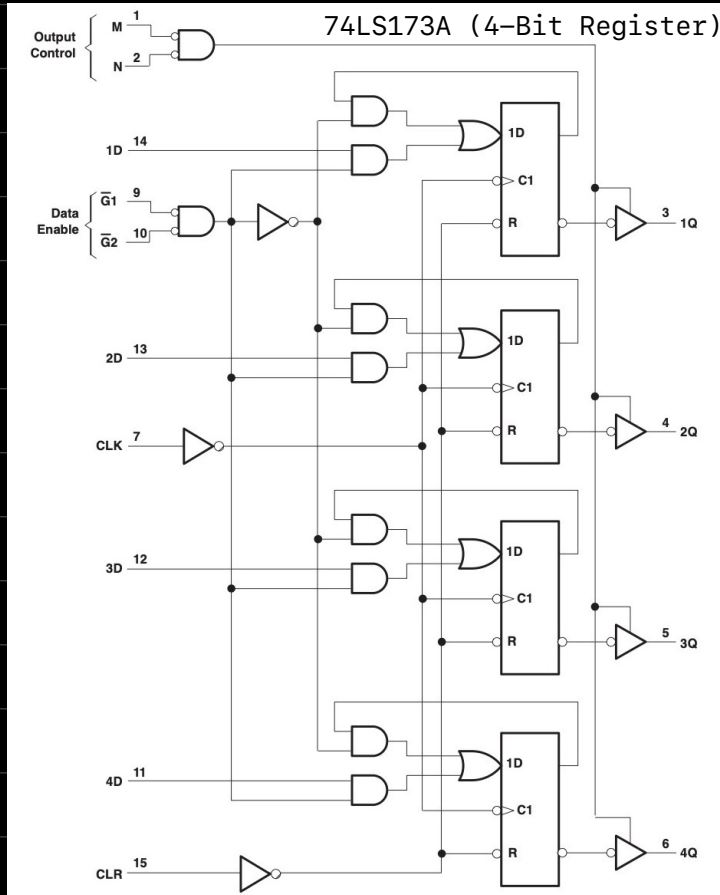
The SELECTION between the ASTABLE (automatic) and the MANUAL pulses is done using a PUSH BUTTON SWITCH which also involves a DEBOUNCING mechanism.

The computer is powered up in the MANUAL pulse mode.

IMMEDIATELY AFTER the computer is powered up, while the initial PROPAGATIONS have NOT completed, the values of the SELECT, the ASTABLE PULSE, the MANUAL PULSE and the HALT inputs FLOATING (at 0, 1 or somewhere between 0 & 1, or oscillating among 0, 1 and somewhere between 0 & 1), WILL NOT cause problems, as the initial PROPAGATIONS will get completed only a VERY SHORT while AFTER the computer is powered up.

After the program to be run is MANUALLY programmed into the RAM, when the MANUAL clock is switched to the AUTOMATIC clock, then it is ASSUMED that the signals NOT propagating in time will NOT happen, EVEN if the switching is done at a time when the ASTABLE PULSE is nearing its NEGATIVE edge-transition, possibly creating a SHORTER clock pulse than required.

A Register (8 Bits), B Register (8 Bits), Memory Address Register (4 Bits), Instruction Register (8 Bits) and Flags Register (2 Bits)



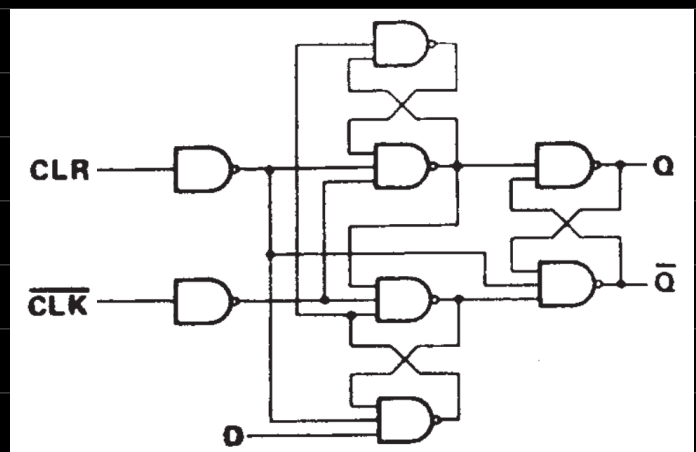
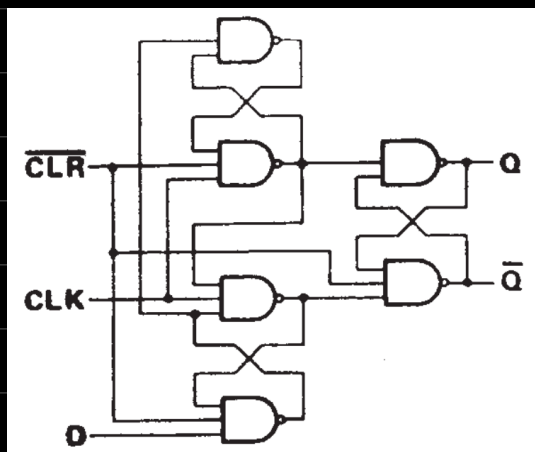
The M and N inputs of EVERY 74LS173A are ALWAYS 0, making the outputs of EVERY 74LS173A ALWAYS enabled, and EXTERNAL tri-state buffers (74LS245) are used.

The DIR input of EVERY 74LS245 is ALWAYS 1/0, fixing the DIRECTION to be from A to B / B to A.

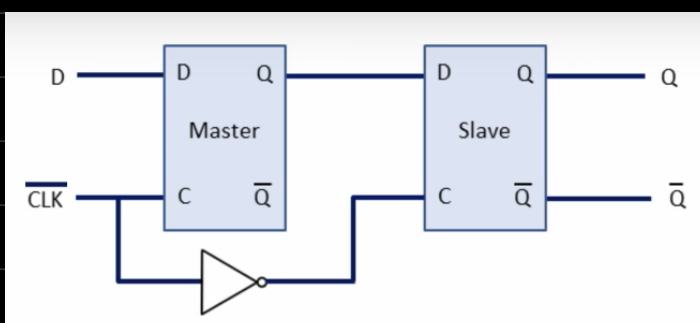
As opposed to for OTHER inputs/outputs, where a SMALL CIRCLE means that the corresponding input/output is INVERTED, a SMALL CIRCLE in the CLOCK input of a FLIP-FLOP DOESN'T mean that the CLOCK input is INVERTED. It ONLY specifies the type of the FLIP-FLOP (NEGATIVE, as opposed to POSITIVE, edge-triggered).

Even though the 74LS173A is POSITIVE edge-triggered, it uses truly NEGATIVE edge-triggered D flip-flops with ACTIVE HIGH clear inputs because there is an INVERTER after the CLOCK input.

Such a flip-flop can be constructed using a truly POSITIVE edge-triggered D flip-flop with an ACTIVE LOW clear input by INVERTING the clock & clear inputs as follows -



Moreover, INSTEAD of being constructed using the ABOVE flip-flops, the 74LS173A can ALSO be constructed using MASTER-SLAVE flip-flops (with GATED D LATCHES as the MASTER latches) such that the MASTER latches work when the REGISTER's CLOCK input becomes 0 and the SLAVE latches work when the REGISTER's CLOCK input becomes 1.



This is a MASTER D - SLAVE D flip-flop which is ALSO an example of a truly NEGATIVE edge-triggered D flip-flop.

The DIFFERENCE between the MEMORY ADDRESS & FLAGS REGISTERS and the OTHER REGISTERS is that the MEMORY ADDRESS & FLAGS REGISTERS DON'T need to output ANYTHING onto the BUS, and hence they DON'T need EXTERNAL tri-state buffers.

The DIFFERENCE between the INSTRUCTION REGISTER and the A & B REGISTERS is that the 4 MOST SIGNIFICANT output wires from the INSTRUCTION REGISTER's 74LS173A are NOT connected to its 74LS245.

So, these DISCONNECTED inputs of the INSTRUCTION REGISTER's 74LS245 MAY remain FLOATING somewhere between 0 & 1.

In this case, there MAY be a problem if the values on the corresponding wires of the BUS would be FLOATING (at 0, 1 or somewhere between 0 & 1, or oscillating among 0, 1 and somewhere between 0 & 1) when the BUS is NOT being driven. This is because for the LDI (Load Immediate) instruction, the A REGISTER would be LOADING the values present on the BUS coming from the INSTRUCTION REGISTER, INCLUDING the 4 MOST SIGNIFICANT bits.

This problem may STILL occur EVEN THOUGH the BUS is constructed such that the values on its wires become 0's when the BUS is NOT being driven. This is because the DISCONNECTED inputs of the INSTRUCTION REGISTER's 74LS245 MAY remain FLOATING at 1, instead of FLOATING at 0 or somewhere between 0 & 1.

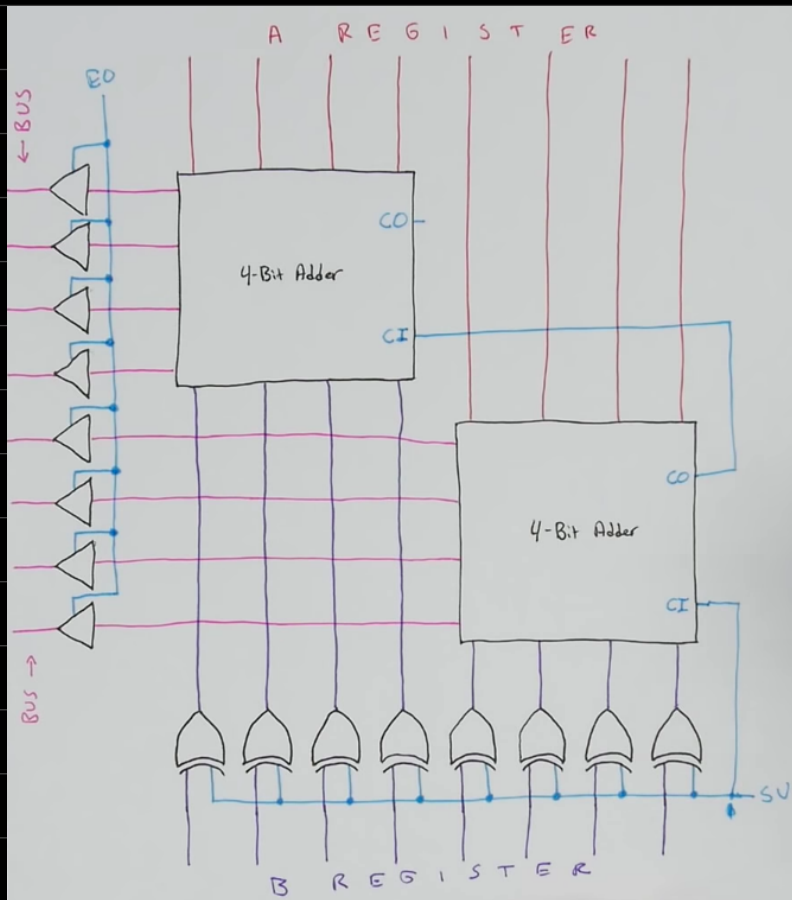
So, DURING the LDI instruction's execution, every such DISCONNECTED input FLOATING at 1 would cause the value on the corresponding BUS wire to become 1.

So, the ONLY solution to this problem is to FIX the inputs of the 4 MOST SIGNIFICANT tri-state buffers of the INSTRUCTION REGISTER's 74LS245 to 0's.

Doing so will ALSO ensure that there would be NO problems EVEN IF the values on the wires of the BUS would be FLOATING when the BUS is NOT being driven.

In general, for ALL ICs, ALL unused INPUTS should be FIXED at 0's or 1's, EVEN FOR unused LOGIC GATES, and ALL unused OUTPUTS should remain DISCONNECTED.

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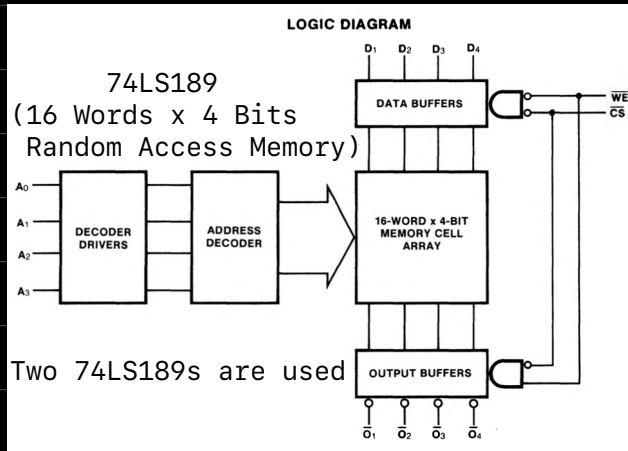
The 4-bit adders correspond to 74LS283's, which use LOOK-AHEAD carry generation.

The tri-state buffers correspond to the ALU's 74LS245.

During the ADD/SUB instruction's execution, the new SUM/DIFFERENCE doesn't keep on getting loaded into the A REGISTER because by the time the new SUM/DIFFERENCE gets generated and gets fed to the D inputs of the A REGISTER, the HOLD TIME of the A REGISTER's flip-flops already EXPIRES.

Similarly, by the time the D inputs of the FLAGS REGISTER get changed, the HOLD TIME of the FLAGS REGISTER's flip-flops already EXPIRES.

Random Access Memory (16 Words x 8 Bits)

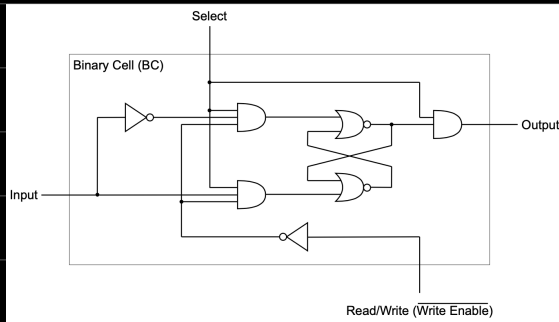


The CHIP SELECT input of EACH 74LS189 is ALWAYS 0, and EXTERNAL tri-state buffers (74LS245) are used.

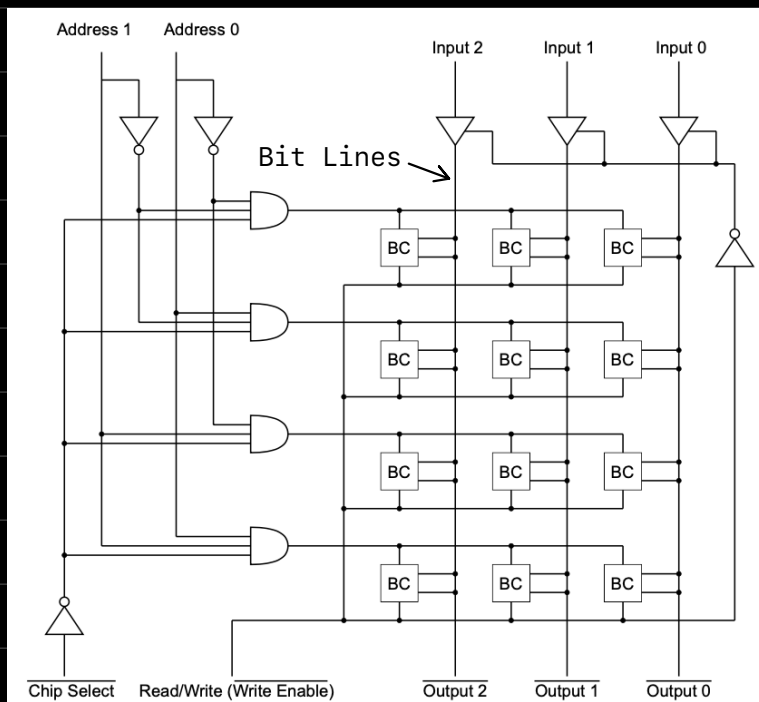
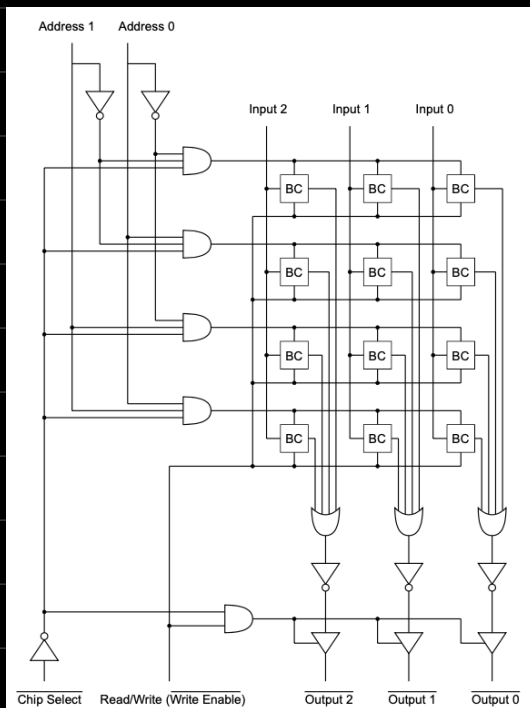
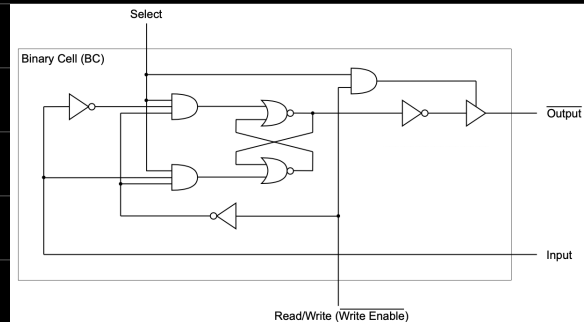
For some reason, the OUTPUTS of the 74LS189 are INVERTED.

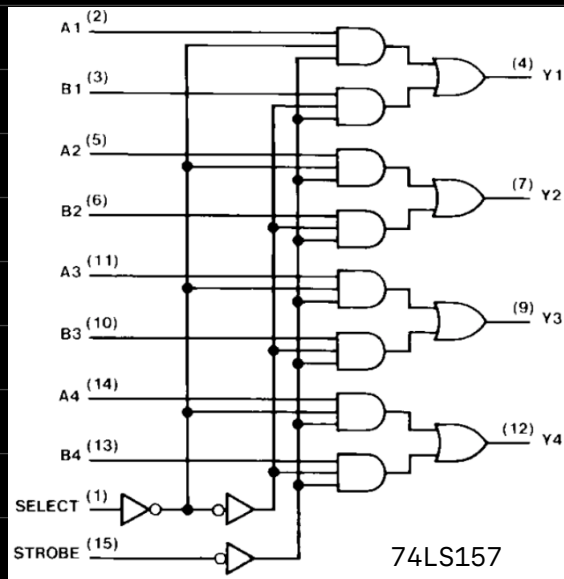
So, EXTERNAL inverters are used to get the correct OUTPUTS.

Implementation 1 (4 Words x 3 Bits)



Implementation 2 (4 Words x 3 Bits)





The ADDRESS inputs, the DATA inputs and the WRITE ENABLE input come from the outputs of EXTERNAL MULTIPLEXERS in order to enable switching between MANUAL mode and RUN mode.

The STROBE (ENABLE) input of EVERY 74LS157 is ALWAYS 0, making EVERY 74LS157 ALWAYS enabled.

During MANUAL mode, the ADDRESS and the DATA come from DIP SWITCHES, and the WRITE ENABLE input comes from the PUSH BUTTON. During RUN mode, the ADDRESS comes from the MEMORY ADDRESS REGISTER and the DATA come from the BUS.

The SELECTION between the two modes is done using a PUSH BUTTON SWITCH.

The REGISTERS consist of D FLIP-FLOPS, whereas the RAM consists of GATED D LATCHES (with SLIGHT modifications). So, for the RAM, EDGE-TRIGGERING is achieved using the RESISTOR-CAPACITOR method.

Also, since the RAM DOESN'T have any LOAD input, therefore the CLOCK input (after using the RESISTOR-CAPACITOR method) is NANDed with the RAM IN signal to become the WRITE ENABLE input of the RAM during RUN mode.

Due to DIFFERENT propagation delays of LOGIC GATES,

1a. For implementation 1, when the ADDRESS changes while WRITE ENABLE is 1, BINARY CELLS from DIFFERENT words MAY get selected SIMULTANEOUSLY for a VERY SHORT amount of time.

1b. For implementation 2, such a situation MAY cause CONTENTION on the BIT LINES for a VERY SHORT amount of time, NOT causing any damage to the BIT LINES.

2a. For implementation 1, when the ADDRESS changes while WRITE ENABLE is 1, it MAY happen that NO BINARY CELL is selected for a VERY SHORT amount of time.

2b. For implementation 2, such a situation MAY cause the values on the BIT LINES to be FLOATING (at 0, 1 or somewhere between 0 & 1, or oscillating among 0, 1 and somewhere between 0 & 1) for a VERY SHORT amount of time.

3a. For implementation 2, when WRITE ENABLE is switched from 1 to 0, the tri-state buffers at the INPUTS MAY become ENABLED SLIGHTLY before the tri-state buffers in the BINARY CELLS become DISABLED, possibly causing CONTENTION on the BIT LINES.

3b. Similarly, when WRITE ENABLE is switched from 0 to 1, the tri-state buffers at the INPUTS MAY become DISABLED SLIGHTLY after the tri-state buffers in the BINARY CELLS become ENABLED, possibly causing CONTENTION on the BIT LINES.

However, such situations would last ONLY for VERY SHORT amounts of time, NOT causing any damage to the BIT LINES.

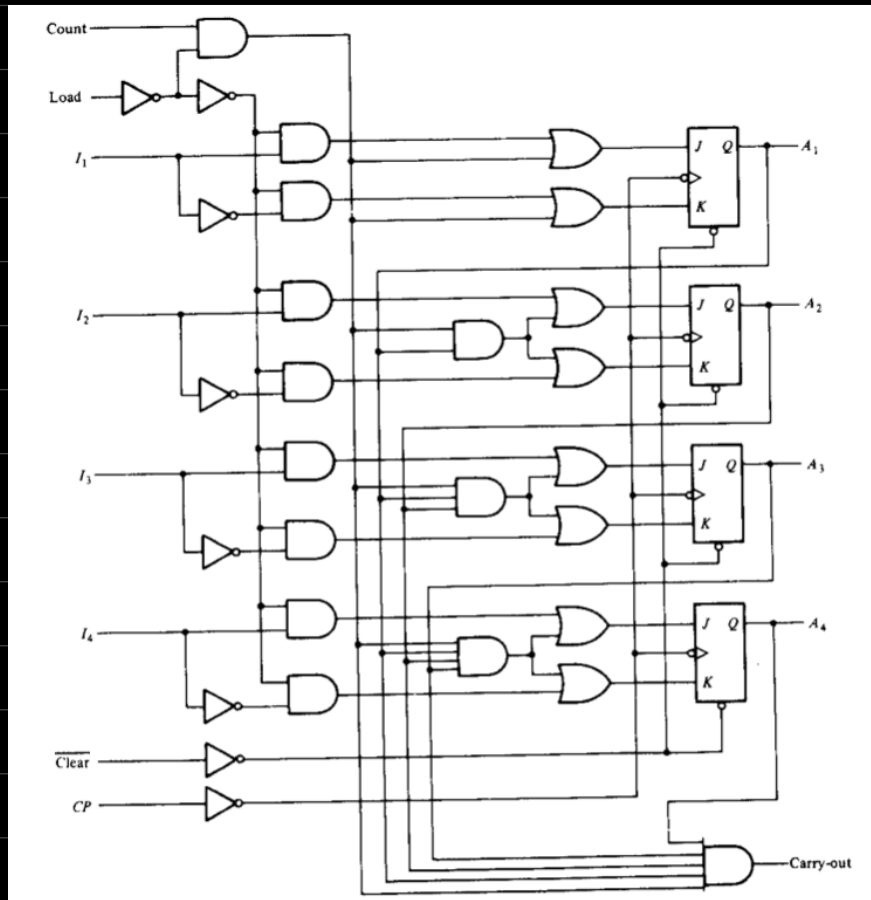
4a. For implementation 2, when WRITE ENABLE is switched from 1 to 0, the tri-state buffers at the INPUTS MAY become ENABLED SLIGHTLY after the tri-state buffers in the BINARY CELLS become DISABLED, possibly causing the values on the BIT LINES to be FLOATING (at 0, 1 or somewhere between 0 & 1, or oscillating among 0, 1 and somewhere between 0 & 1) for a VERY SHORT amount of time. However, ONCE the tri-state buffers at the INPUTS become ENABLED, CORRECT values will get written into the latches, even though the INPUTS of the latches were possibly FLOATING previously. This is because, for eg., for the NOR-gate SR latch, after S and R become CONSTANT at 1/0 and 0/1, respectively, then NO MATTER the current state of the latch, it will result in a STABLE SET/CLEAR state after a LONG ENOUGH time.

4b. Similarly, when WRITE ENABLE is switched from 0 to 1, the tri-state buffers at the INPUTS MAY become DISABLED SLIGHTLY before the tri-state buffers in the BINARY CELLS become ENABLED, possibly causing a FLOATING value to get written to some latch due to the PROPAGATION DELAY of the middle INVERTER inside the BINARY CELL.

The POSSIBILITY of FLOATING values getting written to the latches can be AVOIDED by ENSURING that such a situation does NOT occur, for eg., by adding BUFFERS or an EVEN number of INVERTERS to the RIGHT-MOST wire in order to INCREASE the propagation delay. Doing so will ALSO ensure that there WILL be CONTENTION on the BIT LINES (see 3b). However, such a CONTENTION will cause NO problems, as the OUTPUTS of the SELECTED BINARY CELLS will be the SAME as the INPUTS.

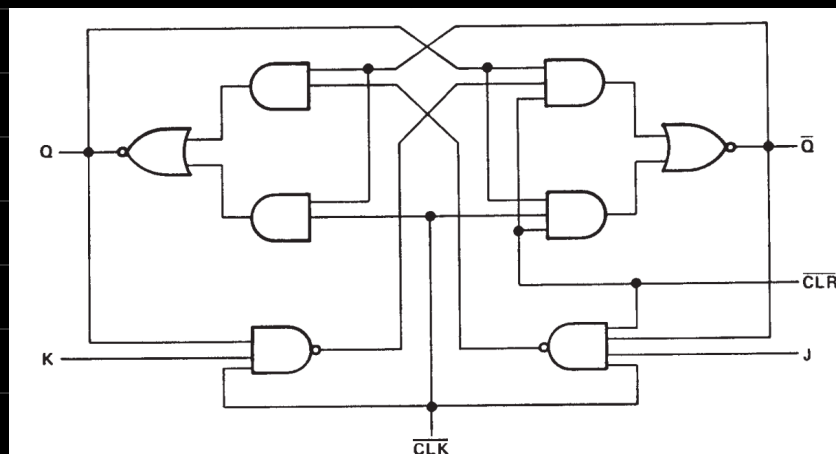
The ADDRESS of the RAM changes ONLY while $\overline{\text{WRITE ENABLE}}$ is (and has been) 1, and $\overline{\text{WRITE ENABLE}}$ changes from 1/0 to 0/1 ONLY while the ADDRESS is (and has been) STABLE.

Program Counter (4 Bits) and Step Counter (4 Bits)



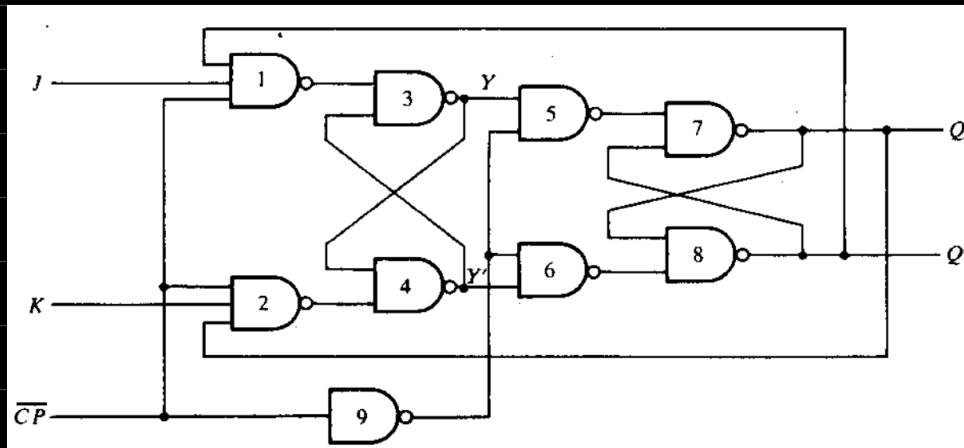
This is a POSITIVE edge-triggered 4-bit SYNCHRONOUS counter (similar to 74LS161).

Even though it is POSITIVE edge-triggered, it uses truly NEGATIVE edge-triggered JK flip-flops with ACTIVE LOW clear inputs because there is an INVERTER after the CLOCK input.



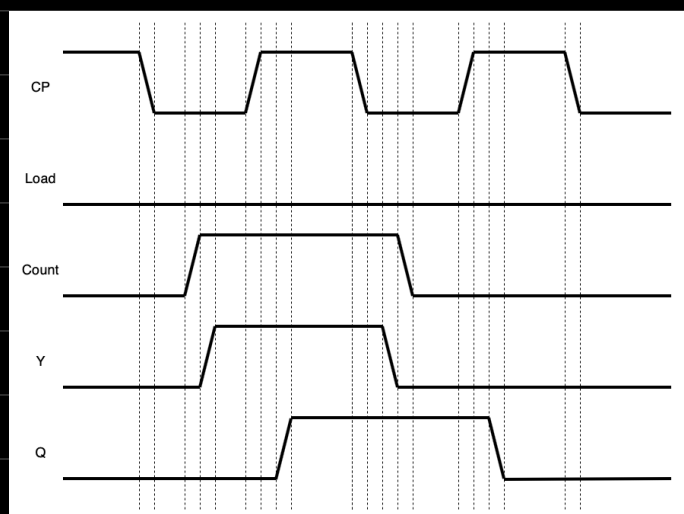
This is a truly NEGATIVE edge-triggered JK flip-flop with an ACTIVE LOW clear input.

However, INSTEAD of using truly NEGATIVE edge-triggered JK flip-flops, using MASTER-SLAVE flip-flops (with GATED JK LATCHES as the MASTER latches) such that the MASTER latches work when the COUNTER's CLOCK input becomes 0 and the SLAVE latches work when the COUNTER's clock input becomes 1 WILL cause problems for the PROGRAM COUNTER.



This is the aforementioned MASTER-SLAVE flip-flop which is NOT an example of a truly NEGATIVE edge-triggered JK flip-flop.

The problem with using these MASTER-SLAVE flip-flops in the PROGRAM COUNTER is that such flip-flops REQUIRE the J & K inputs to stay CONSTANT for the ENTIRE time the MASTER latches are ENABLED (i.e. when the PROGRAM COUNTER's CLOCK input is 0), and the PROPAGATION delays of the CONTROL UNIT WILL cause the J & K inputs to change MIDWAY. Such a situation WILL cause the PROGRAM COUNTER to count TWICE.



This is a TIMING DIAGRAM which illustrates this problem.

CP, Load & Count are inputs of the PROGRAM COUNTER, Y is the output of a MASTER latch and Q is the output of the corresponding SLAVE latch.

For the PROGRAM COUNTER, EXTERNAL tri-state buffers (74LS245) are used.

Similar to the INSTRUCTION REGISTER, the 4 MOST SIGNIFICANT output wires from the PROGRAM COUNTER's 74LS161 are also NOT connected to its 74LS245.

Instead, the inputs of the 4 MOST SIGNIFICANT tri-state buffers of the PROGRAM COUNTER's 74LS245 are FIXED to 0's, just like they SHOULD'VE been for the INSTRUCTION REGISTER as well.

The STEP COUNTER DOESN'T need to output ANYTHING onto the BUS, and hence it DOESN'T need EXTERNAL tri-state buffers.

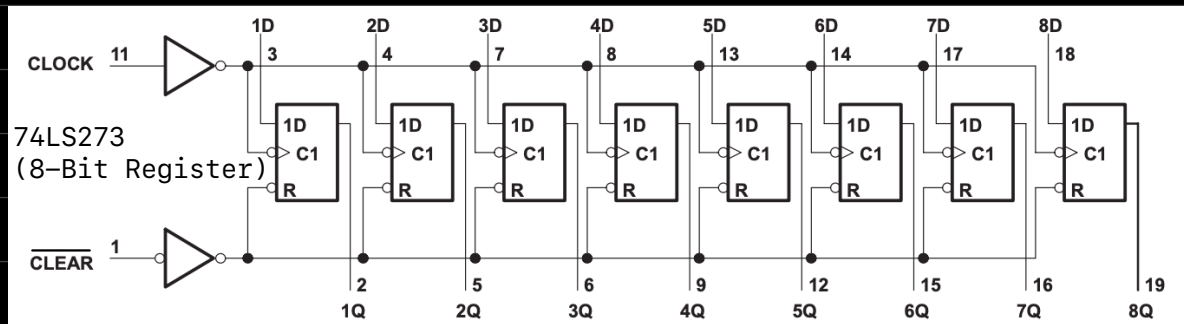
The COUNT (COUNT ENABLE (CE)) and the LOAD (JUMP (J)) inputs of the PROGRAM COUNTER are controlled via the CONTROL UNIT, whereas for the STEP COUNTER, the COUNT input is FIXED to 1 and the LOAD input is FIXED to 0.

A DECODER having INVERTED outputs (74LS138) is used along with the STEP COUNTER (to RESET it when required) because its CLEAR input is ACTIVE LOW.
The $\overline{T5}$ output of the DECODER is used to RESET the STEP COUNTER.

Due to DIFFERENT propagation delays of LOGIC GATES within the DECODER and the STEP COUNTER, when the OUTPUTS of the STEP COUNTER get changed, it MAY happen that $\overline{T5}$ becomes 0 for a VERY SHORT amount of time even when the OUTPUTS of the STEP COUNTER are NOT 101.

However, it is ASSUMED that such a situation will NOT reset the STEP COUNTER ahead of time due to the TIME DURATION for which $\overline{T5}$ will become 0 being EXTREMELY SHORT.
This is because in REAL-WORLD circuits, a CHANGE in the inputs for a SMALL enough time does NOT contain enough ENERGY to cause a LOGIC GATE to SWITCH its output.

Output Register (8 Bits)



The 74LS273 uses NEGATIVE edge-triggered D flip-flops with ACTIVE HIGH clear inputs, just like the 74LS173A.

The OUTPUT REGISTER DOESN'T need to output ANYTHING onto the BUS, and hence it DOESN'T need EXTERNAL tri-state buffers.

Also, as OPPOSED to the 74LS173A, the 74LS273 DOESN'T have any LOAD input, therefore the MAIN CLOCK is ANDed with the OUTPUT REGISTER IN signal to become the CLOCK input of the OUTPUT REGISTER.

The LOGIC DIAGRAM of the 74LS173A is MORE complicated than that of the 74LS273, as it involves EXTRA logic to provide a LOAD input.

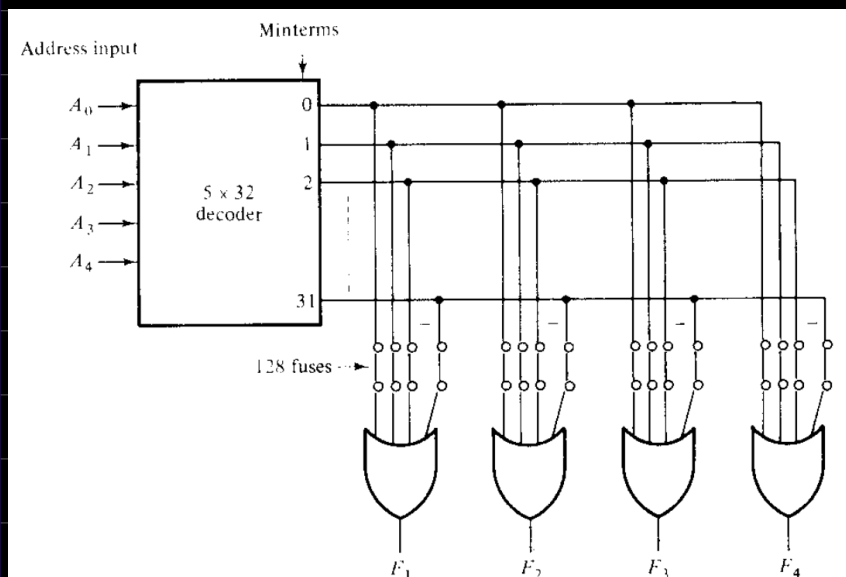
Instead of using the 74LS173A for the A REGISTER, the B REGISTER, the MEMORY ADDRESS REGISTER, the INSTRUCTION REGISTER and the FLAGS REGISTER, the 74LS273 could've ALSO been used instead by ANDing the MAIN CLOCK with the corresponding REGISTER IN signal, as the OUTPUTS of those REGISTERS are ALWAYS enabled anyway.

This is because EVEN THOUGH the insertion of an AND gate would produce PROPAGATION DELAYS between the MAIN CLOCK and the CLOCK inputs of the FLIP-FLOPS, such PROPAGATION DELAYS would cause NO problems.

^ Control Unit

The INSTRUCTION REGISTER's, the STEP COUNTER's and the FLAGS REGISTER's outputs determine the ADDRESS of each EEPROM of the CONTROL UNIT.

After each EEPROM has been PROGRAMMED, its WRITE ENABLE input is FIXED to 1, and its CHIP ENABLE & OUTPUT ENABLE inputs are FIXED to 0's, making each EEPROM ALWAYS enabled.



The above diagram shows a 32-Word x 4-Bit READ-ONLY MEMORY (ROM).

It is ASSUMED that for the OR gates, an INPUT whose link is BROKEN, i.e. a DISCONNECTED input, gets converted to 0, for both IDEAL and REAL-WORLD circuits.

The internal construction of this ROM is SIMILAR to the aforementioned Implementation 1 of the RAM.

An EEPROM's internal construction MAY be similar to the aforementioned Implementation 1 or Implementation 2 (using tri-state buffers) of the RAM, or it MAY be something else ENTIRELY.

	For those EEPROMs whose internal constructions are SIMILAR to the aforementioned implementations of the RAM, due to DIFFERENT propagation delays of LOGIC GATES,
	1a. For implementation 1, when the ADDRESS changes, MULTIPLE decoder outputs MAY get enabled SIMULTANEOUSLY for a VERY SHORT amount of time.
	1b. For implementation 2, such a situation MAY cause CONTENTION on the OUTPUT LINES for a VERY SHORT amount of time, NOT causing any damage to the OUTPUT LINES.
	2a. For implementation 1, when the ADDRESS changes, it MAY happen that NO decoder output is selected for a VERY SHORT amount of time.
	2b. For implementation 2, such a situation MAY cause the values on the OUTPUT LINES to be FLOATING (at 0, 1 or somewhere between 0 & 1, or oscillating among 0, 1 and somewhere between 0 & 1) for a VERY SHORT amount of time.
	Such situations MAY cause MULTIPLE OUT signals to become ENABLED simultaneously for a VERY SHORT amount of time, NOT causing any damage to the BUS wires.
	However, there would be NO problems of ARBITRARY values getting loaded into GATED LATCHES / FLIP-FLOPS due to such situations, because for EVERY component, the CLOCK input being 0, or the CLOCK input being 1 but its POSITIVE edge-transition having gone by, would determine the OUTPUT(s) of the corresponding logic gate(s) IRRESPECTIVE of the input(s) coming from the BUS and the CONTROL UNIT (even FLOATING (at 0, 1 or somewhere between 0 & 1, or oscillating among 0, 1 and somewhere between 0 & 1)).
	Similarly, it is ASSUMED that HLT becoming 1 due to such situations will NOT halt the computer ahead of time due to the TIME DURATION for which HLT will become 1 being EXTREMELY SHORT.
	This is because in REAL-WORLD circuits, a CHANGE in the inputs for a SMALL enough time does NOT contain enough ENERGY to cause a LOGIC GATE to SWITCH its output.

If a component's OUT signal is currently ENABLED, i.e. if it is currently outputting its contents onto the BUS, and if its OUT signal becomes DISABLED according to the NEXT CONTROL WORD, then the propagation delays of that component's EXTERNAL tri-state buffers MAY cause that component to STOP outputting its contents onto the BUS AFTER some other component's OUT signal becomes ENABLED according to that NEXT CONTROL WORD, POSSIBLY causing the two components to output their contents onto the BUS SIMULTANEOUSLY, causing BUS CONTENTION.

However, such a situation would last ONLY for a VERY SHORT amount of time, NOT causing any damage to the BUS wires.

Now, IMMEDIATELY AFTER the computer is powered up, while the initial PROPAGATIONS have NOT completed, the values on MOST of the wires (except for those which are DIRECTLY fixed to 0's/1's) will be FLOATING (at 0, 1 or somewhere between 0 & 1, or oscillating among 0, 1 and somewhere between 0 & 1), including the CONTROL signals (i.e. the OUTPUTS of the CONTROL UNIT's EEPROMs), which MAY cause arbitrary INVALID CONTROL WORDS to get generated one after another.

However, such a situation WILL NOT cause problems, as the initial PROPAGATIONS will get completed only a VERY SHORT while AFTER the computer is powered up.

However, EVEN AFTER the initial PROPAGATIONS get completed, the OUTPUT of every GATED LATCH / FLIP-FLOP will be ARBITRARY (0, 1, OSCILLATING between 0 & 1 or even FLOATING somewhere between 0 & 1).

So, if some OUTPUTS of the INSTRUCTION REGISTER, the STEP COUNTER or the FLAGS REGISTER are OSCILLATING between 0 & 1, then arbitrary, although VALID, CONTROL WORDS MAY get generated one after another EVEN AFTER the initial PROPAGATIONS get completed.

In the WORST case, if all OUTPUTS of the INSTRUCTION REGISTER, the STEP COUNTER and the FLAGS REGISTER are FLOATING somewhere between 0 & 1, then all CONTROL signals (i.e. all OUTPUTS of the CONTROL UNIT's EEPROMs) will become FLOATING (at 0, 1 or somewhere between 0 & 1, or oscillating among 0, 1 and somewhere between 0 & 1), which MAY cause arbitrary INVALID CONTROL WORDS to get generated one after another. Due to this, MULTIPLE OUT signals may become ENABLED SIMULTANEOUSLY for a LONG TIME, causing BUS CONTENTION and DAMAGING the BUS WIRES.

This is because, for eg., if BOTH inputs of an OR gate become FLOATING somewhere between 0 & 1, then after its PROPAGATION delay, its OUTPUT will become FLOATING (at 0, 1 or somewhere between 0 & 1, or oscillating among 0, 1 and somewhere between 0 & 1) if its OUTPUT is NOT being driven by some other component.

Similarly, for the CONTROL UNIT's EEPROMs, in the WORST case, the OUTPUTS of ALL internal LOGIC GATES (or equivalent) may become FLOATING somewhere between 0 & 1, causing the FINAL OUTPUTS to become FLOATING (at 0, 1 or somewhere between 0 & 1, or oscillating among 0, 1 and somewhere between 0 & 1).

So, the ONLY solution to this problem is to CLEAR all of the FLIP-FLOPS as soon as POSSIBLE after the computer is powered up.

In REAL-WORLD computers, IMMEDIATELY AFTER the computer is powered up, a POWER-ON-RESET GENERATOR starts sending RESET signals to CLEAR all of the FLIP-FLOPS. After some time when the power STABILIZES, the initial PROPAGATIONS get completed and all of the FLIP-FLOPS get cleared, the POWER-ON-RESET GENERATOR stops sending the RESET signals and starts the MAIN CLOCK.

^	Startup Behaviour
	AFTER the computer is powered up and AFTER the initial PROPAGATIONS get completed, the
	MAIN CLOCK becomes 0, and the RESET button is pressed, which CLEARS ALL of the FLIP-
	FLOPS, making their OUTPUTS 0's.
	Hence, for every GATED LATCH of the RAM, the output will remain ARBITRARY (0, 1,
	OSCILLATING between 0 & 1 or even FLOATING somewhere between 0 & 1).
	When required, the contents of the RAM will be written to. Doing so will NOT cause a
	problem because, for eg., for the NOR-gate SR latch, after S and R become CONSTANT at
	1/0 and 0/1, respectively, then NO MATTER the current state of the latch, it will
	result in a STABLE SET/CLEAR state after a LONG ENOUGH time.
	The time DURATION for which the RESET button is pressed is LONG ENOUGH for
	1. Signals to PROPAGATE through the RESET circuit and then through the individual
	FLIP-FLOPS, CLEARING them and making their OUTPUTS 0's.
	2. Signals to PROPAGATE after the OUTPUTS of the FLIP-FLOPS become 0's.
	3. Signals to PROPAGATE for the CONTROL WORD corresponding to the ADDRESS 0000000000
	(i.e. CO = 1, MI = 1 and ALL OTHER signals = 0's) to get generated.
	4. Signals to PROPAGATE after CO & MI become 1's and ALL OTHER signals become 0's.
	AFTER the RESET button is released, a LONG ENOUGH time passes for the CLEAR inputs of
	ALL of the FLIP-FLOPS to become DISABLED after signals getting PROPAGATED through the
	RESET circuit.
	DURING the time when the D / JK FLIP-FLOPS of the REGISTERS / PROGRAM COUNTER are
	being CLEARED, the $\overline{\text{CLK}}$ input of EVERY flip-flop will be 1. So, AFTER the CLEAR inputs
	become DISABLED, the contents of ALL flip-flops will remain 0's.

The MAIN CLOCK goes through an external INVERTER and then becomes the CP input of the STEP COUNTER.

DURING the time when the JK FLIP-FLOPS of the STEP COUNTER are being CLEARED, the $\overline{\text{CLK}}$ input of EVERY flip-flop will be 0. So, AFTER the CLEAR inputs become DISABLED, the contents of ALL flip-flops will remain 0's.

At EVERY step, BEFORE the $\overline{\text{CLK}}$ input of EVERY flip-flop becomes 0, the D / J & K inputs of the flip-flops will CORRESPOND to the NEXT data to be loaded such that the SETUP time constraint is NOT violated.

Also, AFTER the $\overline{\text{CLK}}$ input of EVERY flip-flop becomes 0, the D / J & K inputs of the flip-flops will remain CONSTANT such that the HOLD time constraint is NOT violated.

AFTER the RESET button is released, the program to be run is MANUALLY programmed into the RAM by SELECTING the MANUAL mode using the PUSH BUTTON SWITCH, SETTING the ADDRESSES and the DATA using the DIP SWITCHES, and WRITING the DATA using the PUSH BUTTON.

A LONG ENOUGH time passes for signals to PROPAGATE BEFORE the PUSH BUTTON used for WRITING is pressed.

Similarly, the time DURATION for which the PUSH BUTTON is pressed is LONG ENOUGH for signals to PROPAGATE.

^

Program Execution

For every UNSIGNED integer, SUBTRACTING 1 from it is the same as ADDING 255 to it.

So, the CARRY FLAG will be 0 ONLY when that UNSIGNED integer is 0.

Let the FOLLOWING program for MULTIPLYING 2 UNSIGNED integers x and y (say, 3 and 5) be MANUALLY programmed into the RAM –

product = 0	Section-1:	0: LDA 14	0000: 0001 1110
until x is 0:	LDA x	1: SUB 12	0001: 0011 1100
load x	SUB 1	2: JC 6	0010: 0111 0110
subtract 1	JC Section-2	3: LDA 13	0011: 0001 1101
store x	LDA product	4: OUT	0100: 1110 0000
load product	OUT	5: HLT	0101: 1111 0000
add y	HLT	6: STA 14	0110: 0100 1110
store product	Section-2:	7: LDA 13	0111: 0001 1101
output product	STA x	8: ADD 15	1000: 0010 1111
	LDA product	9: STA 13	1001: 0100 1101
	ADD y	10: JMP 0	1010: 0110 0000
	STA product	11:	1011:
	JMP Section-1	12: 1	1100: 0000 0001
		13: product	1101: 0000 0000
		14: x	1110: 0000 0011
		15: y	1111: 0000 0101

AFTER this program is MANUALLY programmed into the RAM, the RUN mode is SELECTED and the MANUAL clock is switched to the AUTOMATIC clock by using the PUSH BUTTON SWITCHES.

For EVERY step, a LONG ENOUGH time passes for signals to PROPAGATE before the MAIN CLOCK gets changed from 0/1 to 1/0.

MAIN CLOCK remains 0, execution of LDA 14 begins -

CO & MI become 1's and ALL OTHER control signals become 0's.

The values on the BUS become 0 0 0 0 0 0 0 0.

The D inputs of the FLIP-FLOPS of the MEMORY ADDRESS REGISTER become 0 0 0 0.

MAIN CLOCK becomes 1 -

The contents of the FLIP-FLOPS of the MEMORY ADDRESS REGISTER remain 0 0 0 0, making the ADDRESS inputs of the RAM remain 0 0 0 0.

The J/K inputs of the FLIP-FLOPS of the STEP COUNTER remain 0/0 0/0 0/0 1/1.

CO & MI remain 1's and ALL OTHER control signals remain 0's.

MAIN CLOCK becomes 0 –

The contents of the FLIP-FLOPS of the STEP COUNTER become 0 0 0 1.

The J/K inputs of the FLIP-FLOPS of the STEP COUNTER become 0/0 0/0 1/1 1/1.

CO & MI become 0's, RO, II & CE become 1's and ALL OTHER control signals remain 0's.

The values on the BUS become 0 0 0 1 1 1 1 0.

The D inputs of the FLIP-FLOPS of the INSTRUCTION REGISTER become 0 0 0 1 1 1 1 0.

The J/K inputs of the FLIP-FLOPS of the PROGRAM COUNTER become 0/0 0/0 0/0 1/1.

MAIN CLOCK becomes 1 –

The contents of the FLIP-FLOPS of the INSTRUCTION REGISTER become 0 0 0 1 1 1 1 0.

The contents of the FLIP-FLOPS of the PROGRAM COUNTER become 0 0 0 1.

The J/K inputs of the FLIP-FLOPS of the STEP COUNTER remain 0/0 0/0 1/1 1/1.

RO, II & CE remain 1's and ALL OTHER control signals remain 0's.

MAIN CLOCK becomes 0 -

The contents of the FLIP-FLOPS of the STEP COUNTER become 0 0 1 0.

The J/K inputs of the FLIP-FLOPS of the STEP COUNTER become 0/0 0/0 0/0 1/1.

R0, II & CE become 0's, IO & MI become 1's and ALL OTHER control signals remain 0's.

The values on the BUS become 0 0 0 0 1 1 1 0.

The D inputs of the FLIP-FLOPS of the MEMORY ADDRESS REGISTER become 1 1 1 0.

MAIN CLOCK becomes 1 -

The contents of the FLIP-FLOPS of the MEMORY ADDRESS REGISTER become 1 1 1 0, making the ADDRESS inputs of the RAM become 1 1 1 0.

The J/K inputs of the FLIP-FLOPS of the STEP COUNTER remain 0/0 0/0 0/0 1/1.

IO & MI remain 1's and ALL OTHER control signals remain 0's.

MAIN CLOCK becomes 0 –

The contents of the FLIP-FLOPS of the STEP COUNTER become 0 0 1 1.

The J/K inputs of the FLIP-FLOPS of the STEP COUNTER become 0/0 1/1 1/1 1/1.

IO & MI become 0's, RO & AI become 1's and ALL OTHER control signals remain 0's.

The values on the BUS become 0 0 0 0 0 0 1 1.

The D inputs of the FLIP-FLOPS of the A REGISTER become 0 0 0 0 0 0 1 1.

MAIN CLOCK becomes 1 –

The contents of the FLIP-FLOPS of the A REGISTER become 0 0 0 0 0 0 1 1.

The J/K inputs of the FLIP-FLOPS of the STEP COUNTER remain 0/0 1/1 1/1 1/1.

RO & AI remain 1's and ALL OTHER control signals remain 0's.

MAIN CLOCK becomes 0 –

The contents of the FLIP-FLOPS of the STEP COUNTER become 0 1 0 0.

The J/K inputs of the FLIP-FLOPS of the STEP COUNTER become 0/0 0/0 0/0 1/1.

RO & AI become 0's and ALL OTHER control signals remain 0's.

MAIN CLOCK becomes 1 –

The J/K inputs of the FLIP-FLOPS of the STEP COUNTER remain 0/0 0/0 0/0 1/1.

ALL control signals remain 0's.

MAIN CLOCK becomes 0, execution of SUB 12 begins -

The contents of the FLIP-FLOPS of the STEP COUNTER become 0 1 0 1.

The J/K inputs of the FLIP-FLOPS of the STEP COUNTER become 0/0 1/1 1/1 1/1.

$\overline{T_5}$ becomes 0, causing the FLIP-FLOPS of the STEP COUNTER to be CLEARED.

The contents of the FLIP-FLOPS of the STEP COUNTER become 0 0 0 0.

The J/K inputs of the FLIP-FLOPS of the STEP COUNTER become 0/0 0/0 0/0 1/1.

CO & MI become 1's and ALL OTHER control signals remain 0's.

The values on the BUS become 0 0 0 0 0 0 0 1.

The D inputs of the FLIP-FLOPS of the MEMORY ADDRESS REGISTER become 0 0 0 1.

MAIN CLOCK becomes 1 -

The contents of the FLIP-FLOPS of the MEMORY ADDRESS REGISTER become 0 0 0 1, making the ADDRESS inputs of the RAM become 0 0 0 1.

The J/K inputs of the FLIP-FLOPS of the STEP COUNTER remain 0/0 0/0 0/0 1/1.

CO & MI remain 1's and ALL OTHER control signals remain 0's.

MAIN CLOCK becomes 0 -

The contents of the FLIP-FLOPS of the STEP COUNTER become 0 0 0 1.

The J/K inputs of the FLIP-FLOPS of the STEP COUNTER become 0/0 0/0 1/1 1/1.

CO & MI become 0's, RO, II & CE become 1's and ALL OTHER control signals remain 0's.

The values on the BUS become 0 0 1 1 1 1 0 0.

The D inputs of the FLIP-FLOPS of the INSTRUCTION REGISTER become 0 0 1 1 1 1 0 0.

The J/K inputs of the FLIP-FLOPS of the PROGRAM COUNTER become 0/0 0/0 1/1 1/1.

MAIN CLOCK becomes 1 -

The contents of the FLIP-FLOPS of the INSTRUCTION REGISTER become 0 0 1 1 1 1 0 0.

The contents of the FLIP-FLOPS of the PROGRAM COUNTER become 0 0 1 0.

The J/K inputs of the FLIP-FLOPS of the STEP COUNTER remain 0/0 0/0 1/1 1/1.

RO, II & CE remain 1's and ALL OTHER control signals remain 0's.

MAIN CLOCK becomes 0 –

The contents of the FLIP-FLOPS of the STEP COUNTER become 0 0 1 0.

The J/K inputs of the FLIP-FLOPS of the STEP COUNTER become 0/0 0/0 0/0 1/1.

R0, II & CE become 0's, IO & MI become 1's and ALL OTHER control signals remain 0's.

The values on the BUS become 0 0 0 0 1 1 0 0.

The D inputs of the FLIP-FLOPS of the MEMORY ADDRESS REGISTER become 1 1 0 0.

MAIN CLOCK becomes 1 –

The contents of the FLIP-FLOPS of the MEMORY ADDRESS REGISTER become 1 1 0 0, making the ADDRESS inputs of the RAM become 1 1 0 0.

The J/K inputs of the FLIP-FLOPS of the STEP COUNTER remain 0/0 0/0 0/0 1/1.

IO & MI remain 1's and ALL OTHER control signals remain 0's.

MAIN CLOCK becomes 0 –

The contents of the FLIP-FLOPS of the STEP COUNTER become 0 0 1 1.

The J/K inputs of the FLIP-FLOPS of the STEP COUNTER become 0/0 1/1 1/1 1/1.

IO & MI become 0's, RO & BI become 1's and ALL OTHER control signals remain 0's.

The values on the BUS become 0 0 0 0 0 0 0 1.

The D inputs of the FLIP-FLOPS of the B REGISTER become 0 0 0 0 0 0 0 1.

MAIN CLOCK becomes 1 –

The contents of the FLIP-FLOPS of the B REGISTER become 0 0 0 0 0 0 0 1.

The J/K inputs of the FLIP-FLOPS of the STEP COUNTER remain 0/0 1/1 1/1 1/1.

RO & BI remain 1's and ALL OTHER control signals remain 0's.

MAIN CLOCK becomes 0 –

The contents of the FLIP-FLOPS of the STEP COUNTER become 0 1 0 0.

The J/K inputs of the FLIP-FLOPS of the STEP COUNTER become 0/0 0/0 0/0 1/1.

RO & BI become 0's, SU, EO, AI & FI become 1's and ALL OTHER control signals remain 0's.

The values on the BUS become 0 0 0 0 0 0 1 0.

The D inputs of the FLIP-FLOPS of the A REGISTER become 0 0 0 0 0 0 1 0.

The D inputs of the FLIP-FLOPS of the FLAGS REGISTER become 1 0.

MAIN CLOCK becomes 1 –

The contents of the FLIP-FLOPS of the A REGISTER become 0 0 0 0 0 0 1 0.

The contents of the FLIP-FLOPS of the FLAGS REGISTER become 1 0.

The J/K inputs of the FLIP-FLOPS of the STEP COUNTER remain 0/0 0/0 0/0 1/1.

SU, EO, AI & FI remain 1's and ALL OTHER control signals remain 0's.

MAIN CLOCK becomes 0, execution of JC 6 begins -

The contents of the FLIP-FLOPS of the STEP COUNTER become 0 1 0 1.

The J/K inputs of the FLIP-FLOPS of the STEP COUNTER become 0/0 1/1 1/1 1/1.

$\overline{T5}$ becomes 0, causing the FLIP-FLOPS of the STEP COUNTER to be CLEARED.

The contents of the FLIP-FLOPS of the STEP COUNTER become 0 0 0 0.

The J/K inputs of the FLIP-FLOPS of the STEP COUNTER become 0/0 0/0 0/0 1/1.

CO & MI become 1's and ALL OTHER control signals remain 0's.

The values on the BUS become 0 0 0 0 0 0 1 0.

The D inputs of the FLIP-FLOPS of the MEMORY ADDRESS REGISTER become 0 0 1 0.

MAIN CLOCK becomes 1 -

The contents of the FLIP-FLOPS of the MEMORY ADDRESS REGISTER become 0 0 1 0, making the ADDRESS inputs of the RAM become 0 0 1 0.

The J/K inputs of the FLIP-FLOPS of the STEP COUNTER remain 0/0 0/0 0/0 1/1.

CO & MI remain 1's and ALL OTHER control signals remain 0's.

MAIN CLOCK becomes 0 –

The contents of the FLIP-FLOPS of the STEP COUNTER become 0 0 0 1.

The J/K inputs of the FLIP-FLOPS of the STEP COUNTER become 0/0 0/0 1/1 1/1.

CO & MI become 0's, RO, II & CE become 1's and ALL OTHER control signals remain 0's.

The values on the BUS become 0 1 1 1 0 1 1 0.

The D inputs of the FLIP-FLOPS of the INSTRUCTION REGISTER become 0 1 1 1 0 1 1 0.

The J/K inputs of the FLIP-FLOPS of the PROGRAM COUNTER become 0/0 0/0 0/0 1/1.

MAIN CLOCK becomes 1 –

The contents of the FLIP-FLOPS of the INSTRUCTION REGISTER become 0 1 1 1 0 1 1 0.

The contents of the FLIP-FLOPS of the PROGRAM COUNTER become 0 0 1 1.

The J/K inputs of the FLIP-FLOPS of the STEP COUNTER remain 0/0 0/0 1/1 1/1.

RO, II & CE remain 1's and ALL OTHER control signals remain 0's.

MAIN CLOCK becomes 0 –

The contents of the FLIP-FLOPS of the STEP COUNTER become 0 0 1 0.

The J/K inputs of the FLIP-FLOPS of the STEP COUNTER become 0/0 0/0 0/0 1/1.

RO, II & CE become 0's, IO & J become 1's and ALL OTHER control signals remain 0's.

The values on the BUS become 0 0 0 0 0 1 1 0.

The J/K inputs of the FLIP-FLOPS of the PROGRAM COUNTER become 0/1 1/0 1/0 0/1.

MAIN CLOCK becomes 1 –

The contents of the FLIP-FLOPS of the PROGRAM COUNTER become 0 1 1 0.

The J/K inputs of the FLIP-FLOPS of the STEP COUNTER remain 0/0 0/0 0/0 1/1.

IO & J remain 1's and ALL OTHER control signals remain 0's.

MAIN CLOCK becomes 0 -

The contents of the FLIP-FLOPS of the STEP COUNTER become 0 0 1 1.

The J/K inputs of the FLIP-FLOPS of the STEP COUNTER become 0/0 1/1 1/1 1/1.

IO & J become 0's and ALL OTHER control signals remain 0's.

MAIN CLOCK becomes 1 -

The J/K inputs of the FLIP-FLOPS of the STEP COUNTER remain 0/0 1/1 1/1 1/1.

ALL control signals remain 0's.

MAIN CLOCK becomes 0 –

The contents of the FLIP-FLOPS of the STEP COUNTER become 0 1 0 0.

The J/K inputs of the FLIP-FLOPS of the STEP COUNTER become 0/0 0/0 0/0 1/1.

ALL control signals remain 0's.

MAIN CLOCK becomes 1 –

The J/K inputs of the FLIP-FLOPS of the STEP COUNTER remain 0/0 0/0 0/0 1/1.

ALL control signals remain 0's.

MAIN CLOCK becomes 0, execution of STA 14 begins -

The contents of the FLIP-FLOPS of the STEP COUNTER become 0 1 0 1.

The J/K inputs of the FLIP-FLOPS of the STEP COUNTER become 0/0 1/1 1/1 1/1.

$\overline{T5}$ becomes 0, causing the FLIP-FLOPS of the STEP COUNTER to be CLEARED.

The contents of the FLIP-FLOPS of the STEP COUNTER become 0 0 0 0.

The J/K inputs of the FLIP-FLOPS of the STEP COUNTER become 0/0 0/0 0/0 1/1.

CO & MI become 1's and ALL OTHER control signals remain 0's.

The values on the BUS become 0 0 0 0 0 1 1 0.

The D inputs of the FLIP-FLOPS of the MEMORY ADDRESS REGISTER become 0 1 1 0.

MAIN CLOCK becomes 1 -

The contents of the FLIP-FLOPS of the MEMORY ADDRESS REGISTER become 0 1 1 0, making the ADDRESS inputs of the RAM become 0 1 1 0.

The J/K inputs of the FLIP-FLOPS of the STEP COUNTER remain 0/0 0/0 0/0 1/1.

CO & MI remain 1's and ALL OTHER control signals remain 0's.

MAIN CLOCK becomes 0 –

The contents of the FLIP-FLOPS of the STEP COUNTER become 0 0 0 1.

The J/K inputs of the FLIP-FLOPS of the STEP COUNTER become 0/0 0/0 1/1 1/1.

CO & MI become 0's, RO, II & CE become 1's and ALL OTHER control signals remain 0's.

The values on the BUS become 0 1 0 0 1 1 1 0.

The D inputs of the FLIP-FLOPS of the INSTRUCTION REGISTER become 0 1 0 0 1 1 1 0.

The J/K inputs of the FLIP-FLOPS of the PROGRAM COUNTER become 0/0 0/0 0/0 1/1.

MAIN CLOCK becomes 1 –

The contents of the FLIP-FLOPS of the INSTRUCTION REGISTER become 0 1 0 0 1 1 1 0.

The contents of the FLIP-FLOPS of the PROGRAM COUNTER become 0 1 1 1.

The J/K inputs of the FLIP-FLOPS of the STEP COUNTER remain 0/0 0/0 1/1 1/1.

RO, II & CE remain 1's and ALL OTHER control signals remain 0's.

MAIN CLOCK becomes 0 –

The contents of the FLIP-FLOPS of the STEP COUNTER become 0 0 1 0.

The J/K inputs of the FLIP-FLOPS of the STEP COUNTER become 0/0 0/0 0/0 1/1.

R0, II & CE become 0's, IO & MI become 1's and ALL OTHER control signals remain 0's.

The values on the BUS become 0 0 0 0 1 1 1 0.

The D inputs of the FLIP-FLOPS of the MEMORY ADDRESS REGISTER become 1 1 1 0.

MAIN CLOCK becomes 1 –

The contents of the FLIP-FLOPS of the MEMORY ADDRESS REGISTER become 1 1 1 0, making the ADDRESS inputs of the RAM become 1 1 1 0.

The J/K inputs of the FLIP-FLOPS of the STEP COUNTER remain 0/0 0/0 0/0 1/1.

IO & MI remain 1's and ALL OTHER control signals remain 0's.

MAIN CLOCK becomes 0 –

The contents of the FLIP-FLOPS of the STEP COUNTER become 0 0 1 1.

The J/K inputs of the FLIP-FLOPS of the STEP COUNTER become 0/0 1/1 1/1 1/1.

IO & MI become 0's, AO & RI become 1's and ALL OTHER control signals remain 0's.

The values on the BUS become 0 0 0 0 0 0 1 0.

The D inputs of the RAM become 0 0 0 0 0 0 1 0.

MAIN CLOCK becomes 1 –

The contents of the GATED LATCHES of the RAM at ADDRESS 1 1 1 0 become
0 0 0 0 0 0 1 0.

The J/K inputs of the FLIP-FLOPS of the STEP COUNTER remain 0/0 1/1 1/1 1/1.

AO & RI remain 1's and ALL OTHER control signals remain 0's.

MAIN CLOCK becomes 0 -

The contents of the FLIP-FLOPS of the STEP COUNTER become 0 1 0 0.

The J/K inputs of the FLIP-FLOPS of the STEP COUNTER become 0/0 0/0 0/0 1/1.

AO & RI become 0's and ALL OTHER control signals remain 0's.

MAIN CLOCK becomes 1 -

The J/K inputs of the FLIP-FLOPS of the STEP COUNTER remain 0/0 0/0 0/0 1/1.

ALL control signals remain 0's.

MAIN CLOCK becomes 0, execution of LDA 13 begins -