

# 8. Sequential Logic

An important characteristic of combinational circuits is their inherent finiteness: every combinational circuit

- is composed of finitely many gates;
- has finitely many inputs and outputs;
- has finitely many input-output paths;
- performs finitely many basic logical operations to compute its output;
- takes a finite amount of time -- bounded by its *t<sub>PD</sub>* specification -- to perform its computation;
- and
- has a finite functional specification (in the form of a truth table or finite Boolean expression).

While the finiteness of combinational circuits has some advantages, it limits the set of computations they can perform. We can design, for example, a combinational device capable of adding two 32-bit binary numbers and generating a 32-bit result, a useful building block that will be explored in subsequent chapters.

Suppose, however, we need to add a column of N 32-bit numbers for some N greater than two. We could design a combinational adder having N 32-bit inputs, a task that becomes tedious for large N; but such a device would be incapable of adding N+1 numbers when the need arises. The fixed, finite hardware resources of any combinational device we build will limit the set of computations it can perform by bounding the number of inputs accepted and the number of logical operations performed in the computation.

To deal with a broader set of computations not amenable to such bounds, such as the addition of N numbers for arbitrary finite N, we need a way to somehow relax these bounds. A resourceful accountant faced with this problem would recognise that adding a column of N numbers can be decomposed into a sequence of 2-input additions, each adding a new input to an accumulating sum. In effect, the finiteness constraint of his combinational tool is circumvented by expansion in another dimension: time.

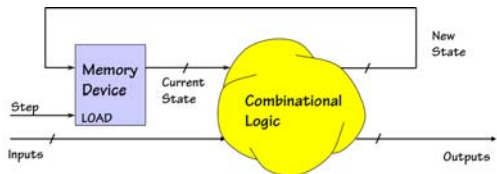
In this chapter, we explore the liberation of our digital circuits from the finiteness bounds of combinational logic by technology and engineering disciplines that allow circuits to perform sequences of consecutive operations. The resulting expanded class of digital circuits are historically called sequential circuits, meaning that they respond to time-ordered sequences of input data rather than producing outputs that reflect only current inputs.

## System State

### 8.1. System State

Our repertoire of combinational devices is clearly missing a critical function if it is to perform useful sequences of operations: memory of some piece of information that persists from one step of the sequence to the next. There needs to be an evolving record of system state, capable of changing from one step of the sequence to the next and of affecting the computation at each step; without such state information, the second and subsequent steps of the sequence would duplicate the first, without any cumulative benefit. The accountant using a 2-input adder to add N numbers must provide this memory of system state -- the accumulating sum -- by means external to his combinational adder; if we are to mechanize his approach in a sequential circuit, we need a device capable of performing an analogous memory function.

One model of sequential circuits is shown to the right. It includes a digital memory device capable of storing some finite number of bits representing the system's current state, as well as a block of combinational logic whose function is to compute both system outputs and a new state from the current state and system inputs. In addition to other binary inputs and outputs, the sequential circuit has a Step input by which it can be instructed to move from one



Sequential Circuit

step in its sequence of operations to the next. When Step is signaled, the memory is loaded with the new state information at its inputs, discarding the previously stored state. Conceptually, the system moves from the state encoded in the previously stored bits to a new state encoded by the bits just loaded into memory.

An important functional distinction between this model and pure combinational logic is that the outputs produced at each step of the sequential circuit’s computation may reflect the current system state as well as the current inputs. The current state will typically reflect some aspect of the system’s history, e.g. the accumulated sum of previously entered addends.

Storage Devices

8.2. Storage Devices

A technology that is missing from our combinational logic toolkit is the memory device needed to communicate state information between steps of our sequence. Many different technologies can be used to effect the storage of digital information, including electromechanical, chemical, audio, and optical approaches; the history of digital systems is rich in interesting and often clever memory designs. Some memory technologies are volatile, holding information for brief periods (so long as power is supplied); others, like magnetic memories or punched cards provide nonvolatile storage.

We present a brief glimpse of two widespread memory technologies in Section 8.4: a volatile approach used for computer main memories using charged capacitors to hold individual bits, as well as nonvolatile magnetic memory used in disk systems for files and other longer-term storage needs.

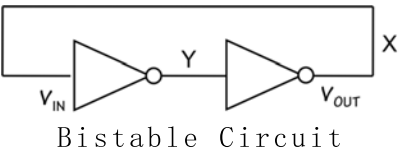
However, the memory technology primarily used for small, short term information like the state of a sequential circuit is typically constructed directly from combinational gates, using carefully-constructed feedback loops to effect a bistable (2-state) digital device. The introduction of cycles (and hence feedback) in circuits of combinational components seems deceptively simple, but requires tedious attention to engineering detail to design provably reliable storage devices. In Section 8.2.1 we endure this tedium once to build a single-bit storage device, the flip flop, and use this as our basic building block for the storage needs of our sequential circuits.

Bistable Circuits

8.2.1. Bistable Circuits

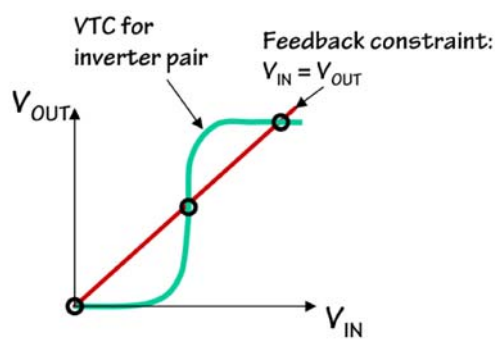
In this section, we will explore the “bootstrapped” construction of memory devices from combinational logic. The key insight behind this construction is that, by introducing cycles in a circuit containing combinational logic, it is easy to create circuits that have multiple stable states in the logic domain.

Consider, for example, the simple two-inverter loop shown to the right. Given our understanding of the behavior of inverters in the logic domain, It is easy to convince oneself that this circuit exhibits two stable states -- with the node marked **X** representing a valid **0** or **1**, respectively, and the other node **Y** representing the opposite value. In fact, this intuition reflects the only two solutions to constraints on these logic values imposed by the specifications of the inverters: namely, that  $X = \bar{Y}$  and  $Y = \bar{X}$ . Which of the two states the circuit is in can be used to store a single bit of information, suggesting an easy path for the creation of simple memory devices using combinational logic.



While this approach can be made to work, the simple logic-domain analysis above seriously understates the engineering complexities involved.

While it is true that the  $X = 0$  and  $X = 1$  states are the only solutions admitted by this circuit in the logic domain, at the circuit level the analysis is more complex. Consider the two-inverter cascade as a single device whose voltage transfer characteristic looks like the green curve shown to the right. This represents one constraint, expressed in the voltage domain, on its input and output voltages  $V_{IN}$  and  $V_{OUT}$ . The feedback connection introduces a second constraint



$V_{IN} = V_{OUT}$ , shown in red on the  $V_{IN}/V_{OUT}$  curve. If we solve these two equations that represent simultaneous constraints on  $V_{IN}$  and  $V_{OUT}$ , we find solutions wherever the two curves cross. We do find solutions corresponding to valid  $X=0$  and  $X=1$  values in the logic domain; however, the geometry of the intersecting curves is such that they inevitably cross at a third point between these two solutions. This third voltage-domain solution represents a problematic unstable equilibrium, and is dealt with at length in Chapter 10. This third equilibrium typically represents an invalid logic level, and sequential circuits require a carefully designed engineering discipline to avoid failures due to propagation

of consequent invalid logic levels.  
D Latch

### 8.2.1.1. D Latch

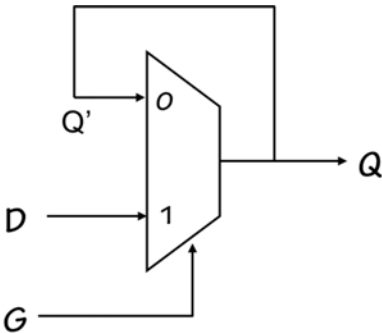
Although we may view the two-inverter loop as a device capable of storing a bit of information, it is of little use unless we can exercise some control over the stored bit. To effect such control, we will use a slightly more complicated combinational device -- a lenient 2-way multiplexor -- in a similar feedback loop as shown to the right. This circuit has a data input  $D$  and a control input  $G$  (for "gate"). The logic-domain analysis of this circuit is, once again, appealingly simple: when  $G=1$ , the logic value on the  $D$  input is selected as the output  $Q$  of the device; when  $G=0$ , the feedback path from the output  $Q$  to the input  $Q'$  is selected. When  $G=0$  there are again two stable solutions in the logic domain:

| $G$ | $D$ | $Q'$ | $Q$ |
|-----|-----|------|-----|
| 0   | --  | 0    | 0   |
| 0   | --  | 1    | 1   |
| 1   | 0   | --   | 0   |
| 1   | 1   | --   | 1   |

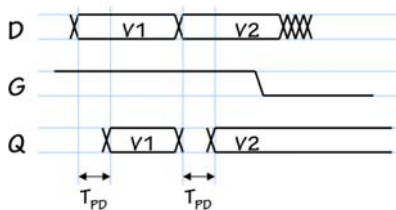
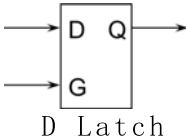
$Q$  stable

$Q$  follows  $D$

$Q = Q' = 0$  and  $Q = Q' = 1$ . Our intention in this design is to use the  $G$  input to switch between two modes of operation detailed to the left: a  $G=0$  mode where the  $Q$  output reflects a stored value, and a  $G=1$  mode in which the value on  $D$  follows a combinational path to the  $Q$  output. This device, called a D Latch, thus behaves as a storage device when  $G=0$  and a "transparent" combinational circuit when  $G=1$ .



The intent is that a  $1 \rightarrow 0$  transition on  $G$  switches from transparent to storage mode, capturing the data currently on  $D$  as the newly stored value.



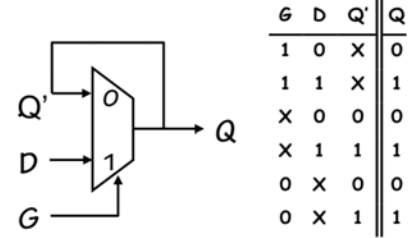
The timing diagram to the left depicts the behavior desired for our latch. While  $G=1$ , the output  $Q$  reflects the value on the  $D$  input after a propagation delay; changes in  $D$  will cause corresponding changes in  $Q$ . If  $G$  becomes 0 while some new value  $V2$  is on  $D$  (and hence  $Q$ ), the latch will store  $V2$  so long as  $G$  remains 0.  
Reliable Latch Operation

### 8.2.1.2. Reliable Latch Operation

Although capturing the  $D$  value on a  $1 \rightarrow 0$  transition of  $G$  may seem intuitively simple, it confronts subtle obstacles that require careful attention and for which lenience plays a critical role. The use of a non-lenient multiplexor in this circuit would imply a period of undefined output after any input change; once  $Q$  is allowed to become invalid, the  $Q'$  input is also invalid, and an invalidity loop may persist even after the  $D$  and  $G$  inputs are both valid. Indeed, even a brief contamination of the  $Q$  output of the mux allows invalid levels to circulate around the feedback loop, losing the stored information; and the mux allows such contamination after any input change.

Use of a lenient multiplexor, whose truth table appears to the right, mitigates this problem by allowing a single input to change under certain circumstances without contaminating the mux output. The three circumstances when a mux input may change without contaminating output validity are:

- $G = 1$ ,  $D = v$  (for  $v = 0$  or  $v = 1$ ) maintained as valid inputs for at least  $t_{PD}$ :  $Q = v$  despite changes in the  $Q'$  input. In this case, the  $D$  input has been selected as the mux output value; thus the value on the other data input is immaterial.
- $D = Q' = v$  (for  $v = 0$  or  $v = 1$ ) maintained as valid inputs for at least  $t_{PD}$ :  $Q = v$  despite changes in the  $G$  input. In this case, the multiplexor is being asked to choose between two identical data inputs, so the value on the select input  $G$  is immaterial.
- $G = 0$ ,  $Q' = v$  (for  $v = 0$  or  $v = 1$ ) maintained as valid inputs for at least  $t_{PD}$ :  $Q = v$  despite changes in the  $D$  input. In this case, the  $Q'$  input has been selected as the mux output value; thus the value on the other data input is immaterial.

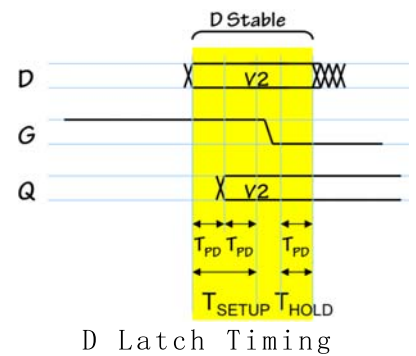


Each of the above lenient-mux guarantees plays a critical role in the reliable behavior of our D latch. The first allows valid  $G = 1$  and  $D$  inputs to force a new value on  $Q$ , independently of its prior stored value. The second allows us to change  $G$  without contaminating the  $Q$  output, a requirement if we are to "latch" the current  $Q$  output. The third allows us to maintain a stored  $Q$  value while  $G = 0$ , independently of changes on  $D$ .

There are additional constraints on the timing of our input signals that must be enforced to ensure reliable latch operation.

To explore the required timing discipline, let's consider the timing of a sequence of input signals that guarantees the loading of some new value,  $V2$ , into a latch made from a lenient multiplexor whose propagation delay is  $t_{PD}$ . We assume that the latch is initially in some unknown state.

1. The new value,  $V2$ , is applied to the  $D$  input while holding  $G = 1$ .
2. After  $D$  and  $G$  have been valid for  $t_{PD}$ , the new value  $V2$  appears at the mux output  $Q$  (and hence at the input  $Q'$ ).
3. After  $D$  and  $G$  have been valid for  $2 \cdot t_{PD}$ , the  $V2$  value on  $Q'$  will have been valid for at least  $t_{PD}$ . Thus, the  $D$  and  $Q'$  inputs are now sufficient to guarantee a valid  $Q = V2$  independently of  $G$ .
4. Continuing to hold  $D = V2$ , we now change  $G$  to 0.  $Q = Q'$  continues to hold a valid  $V2$  during this change.
5. After  $D = V2$  has been valid for another  $t_{PD}$ , the  $G = 0$  and  $Q' = Q$  inputs have been valid for a propagation delay and are hence sufficient to maintain  $Q = V2$  independently of  $D$ . The value  $V2$  is now stored in the latch.



Note that, in order to guarantee that the new value  $V2$  was reliably loaded into the latch, we had to maintain a valid  $D = V2$  input for a period extending from at least  $2 \cdot t_{PD}$  prior to the  $1 \rightarrow 0$  transition on  $G$  through  $t_{PD}$  following that transition. Intuitively, we must guarantee that transitions on the  $D$  and  $G$  inputs to our latch don't come at about the same time: such a race would create a difficult decision problem of the sort discussed in Chapter 10.

To avoid such difficulties, we establish a discipline for the timing of changes on  $D$  relative to the active transition on  $G$  for our latch. In particular, we specify timing parameters  $t_{SETUP}$  and  $t_{HOLD}$  and require that  $D$  must have been stable and valid for an interval that includes

- The setup time  $t_{SETUP}$  before the transition;
- The transition time during which the transition occurs; and
- The hold time  $t_{HOLD}$  after the transition;

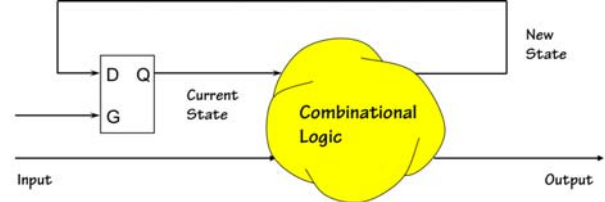
The setup and hold times for our implementation of the latch are  $2 \cdot t_{PD}$  and  $t_{PD}$ , respectively; although other implementations might have different values for  $t_{SETUP}$  and  $t_{HOLD}$ , they will typically enforce the same form of constraint.

## Combinational Cycle Problems

### 8.2.1.3. Combinational Cycle Problems

We might be tempted to try using a latch to store one bit of state for a sequential circuit, as shown to the

right. Indeed, the latch is capable of holding a "current state" bit so long as its  $G = 0$ ; that state is used to compute a "next state" bit applied to the latch's  $D$  input.



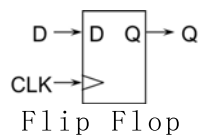
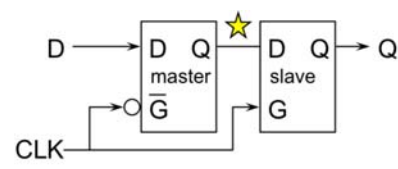
However, loading this "next state" bit into the latch is problematic. Clearly we must raise  $G$  to a valid 1, at least briefly, to load its new value. But for how long must  $G$  remain 1? we note that, while  $G = 1$ , our circuit has a combinational cycle: the combinational logic computes a new state bit, which propagates through the latch to the combinational logic, which then computes a new new state bit, etc. Signals are traveling around this cycle at an uncontrolled rate, and we have no assurance of when (or even if) we can expect valid logic values.

For this reason, latches are rarely used directly as memory devices in our digital circuits. Rather, they are an essential building block for somewhat better behaved flip flops that we will rely on as our basic storage element.

## Edge-triggered Flip Flops

### 8.2.1.4. Edge-triggered Flip Flops

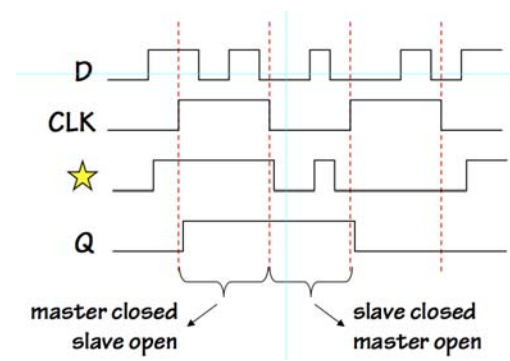
The difficulty in using latches as a memory device in our circuits is that, in their "transparent" mode, they provide a combinational input-output path. We can prevent such a path by cascading two latches and ensuring that they have opposite values on their  $G$  inputs, as shown to the right. The resulting device has a clock input  $CLK$  used to control the flow of data from its  $D$  input to its  $Q$  output. For each value of  $CLK$ , exactly one of the two latches -- the master or the slave -- is transparent; the other holds a stored value on its output.



This device is called an edge-triggered or master-slave flip flop (or simply flip flop or flop) and is depicted as shown on the left. The  $CLK$  input triangle conventionally represents the clock input to a clocked device, a class of sequential devices using edges on their clock inputs to specify timing of critical events such as loading of new data. We will build clocked devices using flip flops and combinational logic.

The flip flop shown above has the effect of loading new data from its  $D$  input on a positive ( $0 \rightarrow 1$ ) transition on its  $CLK$  input.

The diagram to the right shows its behavior given a sequence of changes on its  $CLK$  and  $D$  inputs. As is typically the case, the  $CLK$  input is a periodic square wave. During the  $CLK = 1$  phase of its cycle, the master latch is closed -- outputting its stored value -- while the slave latch is in an open or transparent state, propagating its input value to its output via a combinational path. During the  $CLK = 0$  phase, the master is open (propagating any changes on  $D$  to the input of the slave) while the slave is closed, maintaining a constant flip flop output value.



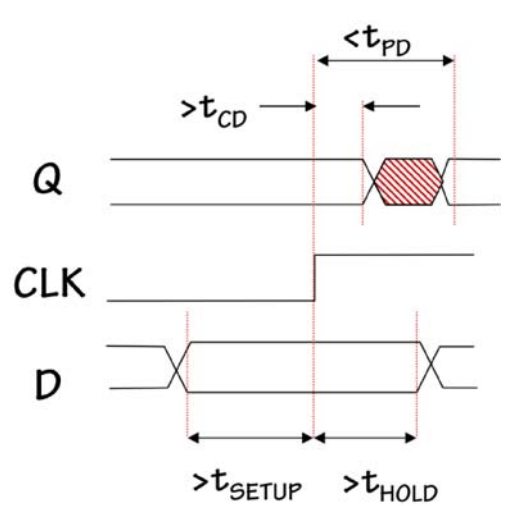
Note that on a positive  $CLK$  transition the master latch goes from open to closed, effectively latching the current data input as its stored value. This value propagates through to the (transparent) slave and hence to the flip flop  $Q$  output. The value is latched by the slave on the subsequent negative transition of  $CLK$ , but the flipflop output remains unchanged since it matches the slave input value. The effect is that the flip flop output value reflects a single stored bit, which is loaded from  $D$  into the flip flop on each positive edge of  $CLK$ .

We can summarize the timing characteristics of the flipflop as shown in the diagram to the right. To load a new value, we again require that the  $D$  input remain stable and valid for an interval that includes prescribed setup and hold times surrounding the active  $CLK$  edge. These values are chosen to ensure that the setup and hold times of the component latches are met.

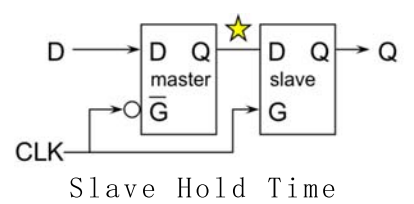
Flip flop timing



We also characterize the timing of the  $Q$  output of the flip flop by familiar propagation and contamination delays. In contrast to the  $t_{PD}$  and  $t_{CD}$  of combinational devices, however, for clocked devices we measure these intervals relative to the active clock edge. Thus, as depicted in the above diagram, the  $Q$  output will maintain its previous value for at least  $t_{CD}$  following the start of an active  $CLK$  edge, and will present the new value no later than  $t_{PD}$  following that edge.



Of course, for reliable operation we must ensure that the timing of the inputs to each latch in the flip flop obeys the setup and hold time constraints specified by the latch. The setup and hold time specifications for the flip flop must cover the setup and hold time requirements of the master latch, which ensures that the setup time requirement of the slave is met as well.



The hold time requirement of the slave, however, imposes a constraint that is less easily controlled. Meeting this constraint involves ensuring that on a negative transition of  $CLK$ , the value on the output of the master latch (the circuit node marked with a star) remain valid for the specified slave hold time. Given that the master becomes transparent on this same clock edge, a transition on this node may happen at about the time of this edge. The only way to guarantee the sufficient hold time is to ensure that the contamination delay of the master latch is sufficient to cover the slave's hold time requirement.

Dynamic Discipline

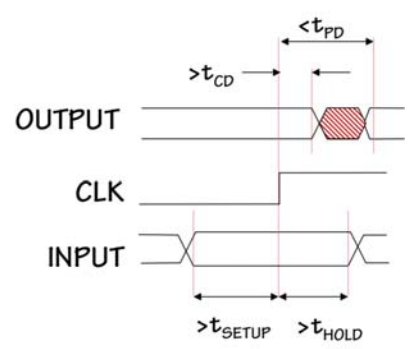
### 8.3. Dynamic Discipline

Our introduction to the Digital Abstraction in Chapter 5 deals with the embedding of an abstract digital domain of 1s and 0s in the physical world of continuous variables. In this move from continuous to discrete values, we observed the unavoidable consequence that not every continuous voltage is a valid representation of a logic level, presenting the problem of designing circuits whose outputs are guaranteed to be valid at least during prescribed intervals. The static discipline of Section 5.3.1 assures that, for combinational circuits, valid inputs lead to valid outputs after an appropriate propagation delay.

Our move to clocked sequential circuits complicates this picture by the introduction of time into our model. Wires now may carry a sequence of valid values separated by periods of invalidity, and we require an additional engineering discipline to reliably distinguish intervals of validity and prevent invalid signals from propagating throughout our circuits.

The setup and hold time constraints derived for our basic clocked building block -- the flip flop -- provide one model for such an additional engineering discipline, and the one that will be followed in this course.

The Dynamic Discipline, summarized in the timing diagram to the right, requires that inputs to a clocked device be stable and valid for a time window surrounding each active clock edge that includes a setup time prior to that edge and a hold time following the edge. If input changes conform to this restriction, output validity is guaranteed outside of specified contamination and propagation delays, measured from the active clock edge (rather than from input changes, as in combinational circuits).



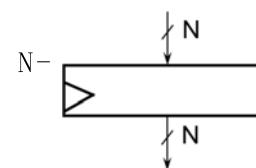
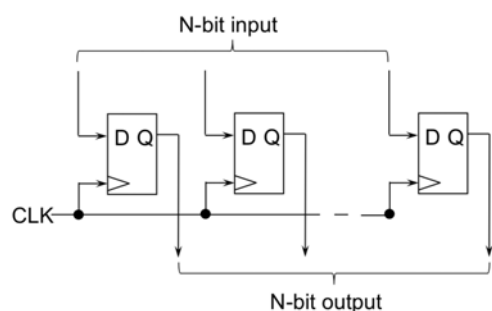
Dynamic Discipline

We can build clocked sequential circuits of arbitrary complexity by combining flip flops with combinational logic.

Registers

#### 8.3.1. Registers

Often we combine  $N$  flip-flops sharing a common clock as shown to the left to make an  $N$ -bit register, a basic clocked storage device capable holding a multi-bit datum. All bits of a register are loaded on the same active clock edge, and are subject to the same setup and hold time requirements with respect to that edge. Register outputs appear simultaneously, again subject to the contamination and propagation delay specifications from the component flip-flops. Registers are denoted in our circuits by the symbol to the right; note the annotations on the data input and output lines to show they represent bundles of  $N$  wires carrying  $N$  bits simultaneously.

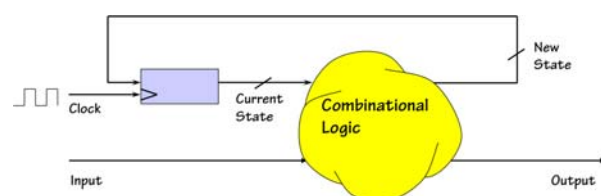


bit Register

Adding logic to clocked devices

### 8.3.2. Adding logic to clocked devices

There are a variety of approaches to building complex sequential systems. A simple approach suggested in Section 8.1 is to use a single multibit register to hold the entire system state, as shown to the left. This approach is convenient for certain sequential circuit applications, and is the basis for the Finite State Machine abstraction discussed in Chapter 9.



Finite State Machine

The dynamic discipline imposed by the register in the above diagram requires that its setup and hold time

requirements,  $t_{SETUP}$  and  $t_{HOLD}$ , be met. Assume that the combinational logic has propagation delay  $t_{PD/LOGIC}$  and contamination delay  $t_{CD/LOGIC}$ , and the propagation and contamination delay specifications for the register are  $t_{PD/REG}$  and  $t_{CD/REG}$  respectively. Then the dynamic discipline requires that

- $t_{PD/REG} + t_{PD/LOGIC} + t_{SETUP}$  be less than the clock period, to assure that the new state data will meet the register setup time requirement;
- $t_{CD/REG} + t_{CD/LOGIC} \geq t_{HOLD}$ , to assure that the register hold time requirement is met;
- The setup time for the input data is at least  $t_{PD/LOGIC} + t_{SETUP}$ , to assure that changes in input data propagate to the register in time to meet its setup time requirement; and
- The hold time requirement for the input data is at least  $t_{HOLD} - t_{CD/LOGIC}$  to assure that input value changes conform to the register hold time requirements.

It is often more convenient to distribute state information of a complex system among various subsystems, allowing the construction of such systems from sequential components. Orderly construction of systems with distributed state -- and management of the exploding number of consequent setup and hold time requirements -- demands the constraints of an additional engineering discipline. While there are several alternatives, the simplest and most common of these is the single clock synchronous discipline presented in Section 8.3.3.

Single Clock Synchronous Discipline

### 8.3.3. Single Clock Synchronous Discipline

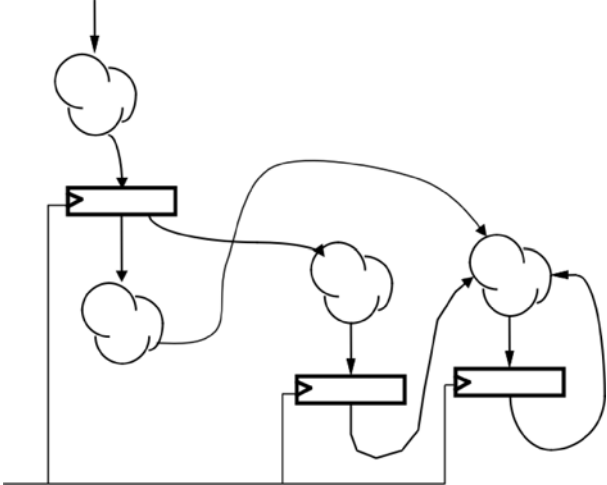
A straightforward approach to engineering sequential systems of arbitrary complexity is to use a single, shared, periodic clock signal to dictate the timing of validity for all signals within the system. We can build such systems from combinational logic and interspersed registers as sketched to the right, so long as a few simple rules are followed. The basic idea is that the active edges of a single clock signal dictates timing of all register reloads throughout the system, and, consequently, the timing of the validity of each register output. Each output typically propagates through some combinational logic to another register, where it must become valid in time to meet the target

Single Clock Synchronous System

register's setup time requirement prior to the next active clock edge. The clock period is then chosen to be sufficiently long to cover the propagation delay and setup time of each such path, assuring that all setup times within the system are met.

In general, the design of a single-clock synchronous system requires that

- Components are combinational devices and clocked devices (i.e., registers).
- The circuit contains no combinational cycles -- every cyclic directed path must go through at least one register (or other clocked device).
- A single clock input to the system directly drives the clock input of each clocked component; no gates or logic may be imposed on clock signals.
- Every internal path (of the form  $REG_{SOURCE} \rightarrow LOGIC \rightarrow REG_{TARGET}$ ) has sufficient contamination delay to cover the hold time requirement of the target register.
- The period of the system clock is sufficiently long to cover the propagation delay along every internal path (again of the form  $REG_{SOURCE} \rightarrow LOGIC \rightarrow REG_{TARGET}$ ) plus the setup time of the target register.
- Each input  $IN$  to the system is subject to a setup time requirement sufficiently long to guarantee that every path of the form  $IN \rightarrow LOGIC \rightarrow REG_{TARGET}$  covers the propagation delay through  $LOGIC$  plus the setup time of the target register.



The tedium of meeting internal hold time requirements can be mitigated by the use of registers whose contamination delay is at least as great as their hold time requirement, assuring that hold times are met in each path between registers. Setup and hold time requirements for inputs to the system are dictated by the paths connecting the inputs to registers, and the timing of system outputs by paths between these outputs and internal registers.

### Synchronous Hierarchy

#### 8.3.4. Synchronous Hierarchy

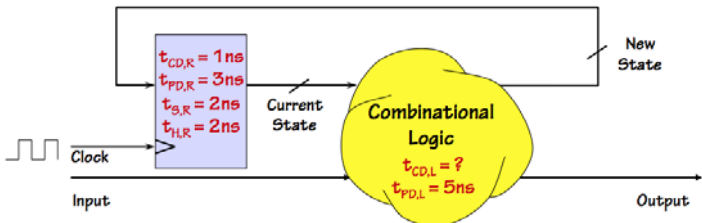
The single-clock synchronous discipline allows, in principle, the use of clocked sequential subsystems as components. Clocked components may themselves follow the single-clock discipline in their internal construction, allowing a hierarchical approach to the design of complex systems. Since all of our single-clock sequential circuits are constructed from flip flops and combinational logic, a hierarchical design can always be "flattened" by expanding each clocked component into a network of flip flops and logic; if the single-clock discipline is uniformly followed by each component, the expanded network will follow that discipline as well.

In practice, however, such flattening is rarely necessary. If appropriate setup and hold time constraints are specified for each component, it follows that meeting these constraints assures that the setup and hold time constraints of each internal register are met as well. It is this property that motivates our generalization of flip flops (or, equivalently, registers) to clocked devices in our single-clock rules.

#### Example: Sequential Circuit Timing

#### 8.3.5. Example: Sequential Circuit Timing

Consider a clocked device constructed from a register and some combinational logic, as diagrammed to the right. The register specifies propagation and contamination delays of 3 and 1 ns, respectively, and requires setup and hold times of 2 ns each; the combinational logic has a propagation delay of 5 ns. We assume a periodic clock input whose active (positive) clock edges occur every  $t_{CLK}$  ns.



Clocked device example

Given these specifications, meeting the registers setup and hold times imposes the following constraints on the timing of our device:



- The feedback path from the register output through the combinational logic to the register input must meet the 2 ns register hold time requirement. This requires that the cumulative contamination delay around this path  $t_{CD,R} + t_{CD,L}$  be at least 2 ns, requiring at least 1 ns of contamination delay for the combinational logic. Unless this requirement is met, we can't expect the circuit to operate reliably.
- In order to meet the setup time requirement along this same feedback path, the clock period  $t_{CLK}$  must be long enough to include the cumulative propagation delays of the register and combinational logic as well as the specified register setup time. Thus  $t_{CLK} \geq t_{PD,R} + t_{PD,L} + t_{S,R} = 10ns$ . The maximum clock frequency is thus  $1/t_{CLK}$  or 100 MHz.
- The path from the Input through the combinational logic to the register must meet the register setup and hold time requirements. To assure this, our device specifies required setup and hold times for the Input line relative to active edges of the supplied clock of  $t_S = t_{PD,L} + t_{S,R} = 7ns$  and  $t_H = t_{H,R} - t_{CD,L} = 1ns$  respectively (assuming the minimum  $t_{CD,L}$  of 1 ns).

Non-CMOS Memory

## 8.4. Non-CMOS Memory

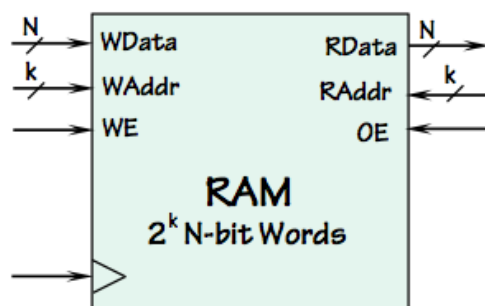
While the CMOS-based flip flops and registers described in section Section 8.2 are well suited to temporary storage of modest-sized digital values (such as state information), other technologies are widely used for larger-scale storage requirements. Certain of these (such as the Dynamic RAM used for computer main memory) are volatile, in that the information contained persists only so long as the memory remains powered and operational. Other technologies such as magnetic or optical disks are non-volatile, and useful for long-term and offline storage.

Most contemporary approaches to mass storage are much more sophisticated than the glimpses given in the following sections might imply. Typically, modern memory pushes bit storage density to the limit, and depends upon error correction (of the sort described in Section 3.4.3) to assure reliable storage.

RAM Arrays

### 8.4.1. RAM Arrays

The term Random Access Memory or RAM refers to a storage device architecture containing some number of  $N$ -bit storage locations that are equally accessible, hence suitable for situations in which they are accessed in random order. Such designs are distinguished, for example from serial-access memory devices (like magnetic or paper tape) that prescribe a preferred order for accessing their stored data.



Random Access Memory

A representative model for a random-access memory component is diagrammed to the left. It is capable of storing  $2^k$   $N$ -bit words of binary data, for specified parameters  $N$  and  $k$ . It is organized (at least conceptually) as an array of  $2^k$  locations, each designated by an integer address in the range  $0..2^k - 1$ . It is typically a clocked device, hence the clock input on its lower left.

The three connections on the upper left constitute a write port, and consist of a  $k$ -bit write address, an  $N$ -bit word of write data, and a write enable control signal. If the write enable is asserted on an active clock edge, the specified  $N$  bits of data will be written into the location specified by

the write address.

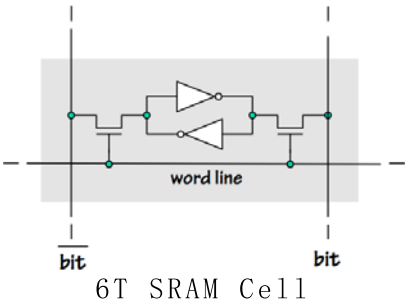
The three connections on the upper right are a read port, and specify the address of an  $N$ -bit word to be read at the next active clock edge. The read port may include an output enable as shown here: a control input that specifies whether the module is to perform a read operation and assert data onto the read data lines at the next active clock edge. The output enable makes it convenient to cascade multiple RAM modules by connecting their ***RData*** outputs.

RAM devices are often implemented as two-dimensional arrays of single-bit memory cells, sharing a common addressing structure much like that of the ROMs described in Section 7.8.3.

8.4.1.1. Static RAM

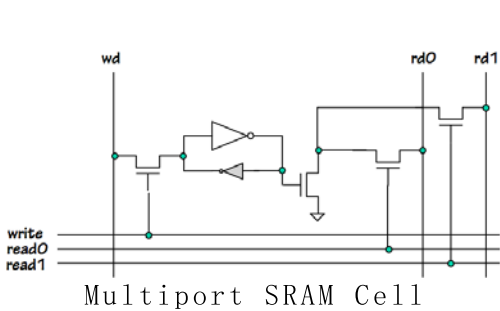
Small fast memory arrays can be built entirely from CMOS gates and registers of the sort described in Section 8.3.1. The design of such memory devices, however, is commonly optimized at the circuit level in ways that violate CMOS rules in the interest of gains in performance and memory density. One such family of memory devices are Static RAMs or SRAMs, named to distinguish them from the dynamic RAMs described in the next section.

A typical SRAM consists of a two-dimensional array of six-transistor cells like that shown on the left. Each row of cells shares a word line, asserted (driven positive) to select all cells in that row for a read or write operation; each column shares two bit lines used to write or read a value to or from a cell in a row selected by the asserted word line. Each cell consists of a pair of cross-coupled inverters -- a simple bistable element -- whose stored value and its complement are connected to the bit lines only when the word line is asserted.



All cells in a row may be read by asserting the corresponding word line, driving the bit lines of each column to voltages reflecting the 1s and 0s stored in each cell. A cell may be written by driving the bit lines with a value and its complement, and momentarily driving the word line. While violating CMOS rules (since opposing outputs are connected to the same circuit node), appropriate choice of transistor sizing and drive parameters allows the bit lines to simply overpower the value stored in the inverter pair, storing a new value.

Many variations and improvements to this SRAM cell design are possible.

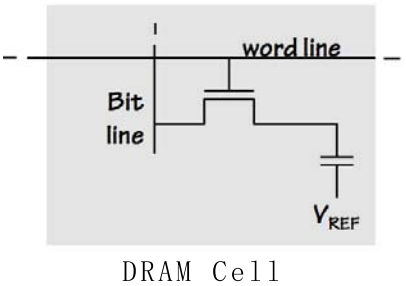


To the left is a cell for a SRAM array having two read ports and one write port, typical of the register files we will be using in the next module of this course. The cell uses a single bit line for a write operation; the use of assymmetric transistor sizes in the inverter pair storing the bit allows its value to be overpowered from one end alone. Each read port is supported by separate word and bit lines, allowing two independently-selected words to be read simultaneously from the array during a single cycle.

Dynamic RAM

8.4.1.2. Dynamic RAM

Demand for large, cheap computer main memories has driven the development of Dynamic RAM or DRAM technology to an extreme that minimizes the size of each memory cell at the cost of sophisticated surrounding circuitry. DRAM stores a single bit of information at each cell in the form of a charge on a capacitor, using a structure like that shown to the right. The bottom terminal on the capacitor is connected to a fixed reference voltage (such as ground), and the other terminal is left "floating" (disconnected) so that no current flow will disturb the stored charge. A single NFET is capable of momentarily connecting the floating end of the capacitor to a vertical bit line; this momentary connection is used both for setting the value stored at the cell and reading the stored value. The cell shown is again one of many arranged in a two-dimensional array, with vertically aligned cells sharing a bit line and horizontal rows sharing word lines.



To store a value in a cell, the appropriate bit line is precharged to the appropriate voltage and the voltage on the word line is raised briefly so that the NFET conducts and charges the capacitor. Once the NFET returns to its usual non-conducting state, the charge on the capacitor will be undisturbed by variation of the bit line voltage.

To read the value stored in the cell the word line is again asserted so that the NFET briefly connects the bitline to the capacitor. In this case, a sensitive sense amplifier connected to the bit line detects the effect of the connection on its voltage, and determines whether the

charge that had been stored on the capacitor represents a zero or a one. The read operation is destructive (since it causes the stored charge to be dissipated), so each read operation is immediately followed by a write operation on the same cell to restore the stored information.

Because there is some leakage of the charge stored in each dynamic RAM cell, DRAMs have to be periodically refreshed. This involves reading each cell and rewriting their values, and leads to the “dynamic” in the name of this technology.

Magnetic and Optical Memories

8.4.2. Magnetic and Optical Memories

Mass memory technologies often involve significant mechanical components; rotating optical and magnetic storage are popular contemporary examples. These devices store bits as cells with persistent magnetic or optical state on a relatively large surface, and use mechanical means to move an optical or magnetic head to the appropriate position to read or record data. Although they can transfer (read or write) data at high rates, they are decidedly not optimized for random access: access to an arbitrary datum on a hard disk, for example, typically requires a time on the order of ten milliseconds. For this reason, rotating disk memory is typically used to access large blocks of data stored in consecutive locations on the media.

Chapter Summary

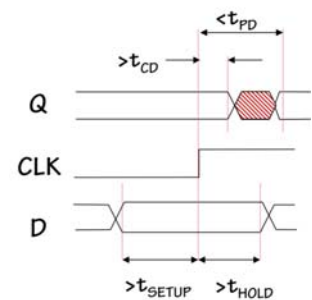
8.5. Chapter Summary

The extension of our digital abstraction to include systems with internal state adds several key concepts:

- 1. The notion that individual signal wires may contain a sequence of potentially different logic values during the course of a computation;
- 2. The use of clock signals whose transitions dictate the timing of transitions between valid logic values on signal wires;
- 3. The need for a dynamic discipline to identify intervals during which signal validity is guaranteed.

Because the design of basic elements with state from basic circuit elements is complex and error prone, we choose to carefully engineer a small repertoire of memory devices and restrict our design of complex sequential systems to a mix of these and combinational devices according to a carefully prescribed discipline. Our memory devices include large dynamic RAM arrays and magnetic/optical storage, as well as flip flops using carefully engineered feedback loops and combinational devices:

- A bistable latch may be constructed using a lenient mulitplexor, and provides provably reliable storage so long as an appropriate timing discipline is followed;
- Latches may be used to construct a flip flop, a single-bit clocked storage device. Flip flops provide reliable storage, again so long as an appropriate dynamic discipline is followed.
- The dynamic discipline for clocked devices involves
  - A clock signal, whose active (positive) edges prescribes allowable times for transitions on other inputs;
  - Setup and Hold times  $t_s$  and  $t_h$ , which establish a window surrounding each active clock transition during which other inputs must be stable and valid; and
  - Propagation and contamination delay specifications  $t_{pd}$  and  $t_{cd}$  on each output, measured from the time of the active clock edge to guarantee intervals of output validity.
- $N$  flip flops can be combined as an  $N$ -bit register, sharing a clock input;
- The single-clock synchronous discipline allows clocked circuit elements to be interspersed with combinational logic, avoiding combinational cycles and sharing a clock signal, to form new clocked components.



Although most of the systems in this subject follow the simple synchronous single-clock discipline outlined here, there are plausible alternatives. This subject is revisited briefly in Section 11.8.