

# Computer Architecture

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Keep in mind there are *two* PDFs available (of which this is the latter):

1. a PDF of examinable material used as lecture slides, and
2. a PDF of non-examinable, extra material:
  - ▶ the associated notes page may be pre-populated with extra, written explanation of material covered in lecture(s), plus
  - ▶ anything with a “grey’ed out” header/footer represents extra material which is useful and/or interesting but out of scope (and hence not covered).

Notes:

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- **Problem:** design a cyclic  $n$ -bit **counter**, i.e., a component whose output  $r$  steps through values

$$0, 1, \dots, 2^n - 1, 0, 1, \dots$$

but is otherwise uncontrolled (or “free running”).

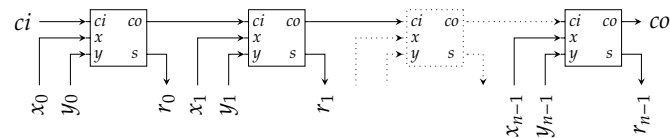
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- (Potential) **solution:** we already have an  $n$ -bit adder that can compute  $x + y$ , i.e.,



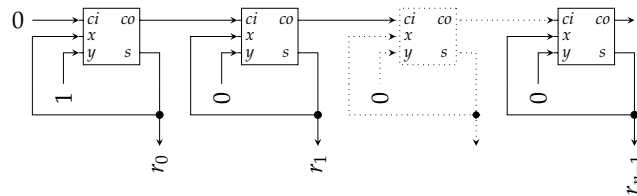
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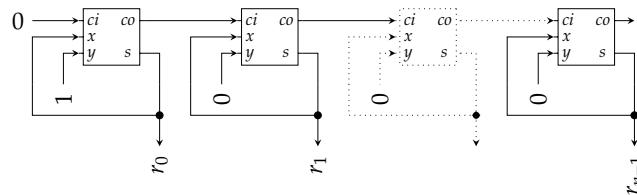
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so we'll just have it compute  $r \leftarrow r + 1$  over and over again;

- (New) **problem:** this **won't work**, because, for example,
  1. we can't initialise the value, and
  2. we don't let the output of each full-adder settle before it's used again as an input.

Notes:

- ▶ (Actual) **problem**: combinatorial logic has some limitations, namely we can't
  - ▶ control *when* a design computes some output (it does so continuously), nor
  - ▶ *remember* the output when produced.
- ▶ (Actual) **solution**, and so **agenda**: **sequential logic** design, where, crucially,
  - ▶ the output is a function of the input plus any state (e.g., stemming from previous inputs),
  - ▶ computation is viewed as being discrete, i.e., step-by-step,

via coverage of

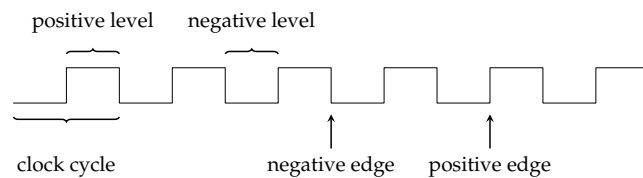
1. synchronisation of components  $\leadsto$  clocks
2. components that maintain state  $\leadsto$  latches, flip-flops, and registers
3. mechanism for computational steps  $\leadsto$  structure plus strategy

Notes:

## Part 1: clocks (1)

- ▶ **Concept**: a **clock** is a signal that oscillates (or alternates) between 1 and 0.

### Definition



where

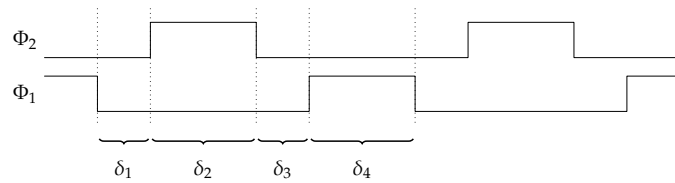
- ▶ the clock signal is typically either
  1. an input which needs to be supplied externally, or
  2. produced internally by a **clock generator**.
- ▶ we use features of the clock to
  1. trigger events (e.g., steps in some sequence of computations), and/or
  2. synchronise components.
- ▶ the **clock frequency** is how many clock cycles happen per-second; it must be
  - ▶ fast enough to satisfy the design goals, yet
  - ▶ slow enough to cope with the critical path of a given step.

Notes:

## Part 1: clocks (2)

► **Concept:** an  $n$ -phase clock is distributed as  $n$  separate signals along  $n$  separate wires.

### Definition



where for  $n = 2$ , for example,

- features in a 1-phase clock (e.g., cycle, levels and edges), generalise to  $\Phi_1$  and  $\Phi_2$ ,
- there is a guarantee that positive levels of  $\Phi_1$  and  $\Phi_2$  don't overlap, and
- the behaviour is parameterisable by altering  $\delta_i$ .

Notes:

## Part 2: latches, flip-flops, and register (1)

### Concepts

### Definition

A bistable component can exist in two stable states, i.e., 0 or 1: at a given point, it can

- retain some **current state**  $Q$  (which can also be read as an output), *and*
  - be updated to some **next state**  $Q'$  (which is provided as an input)
- under control of an **enable signal**  $en$ .

### Definition

The behaviour of a bistable is described by an **excitation table**, and sometimes expressed using a **characteristic equation**: versus, e.g., a truth table, the idea is to capture the notion of time (cf. current and next).

### Definition

A given bistable component controlled by an enable signal  $en$  can be

1. **level-triggered**, i.e., updated by a given level on  $en$ , or
2. **edge-triggered**, i.e., updated by a given edge on  $en$ .

The former type is termed a **latch**, whereas the latter type is termed a **flip-flop**.

Notes:

## Part 2: latches, flip-flops, and register (2)

### Concepts

#### Definition

An “SR” latch/flip-flop component has two inputs  $S$  (or **set**) and  $R$  (or **reset**):

- ▶ when enabled, if
  - ▶  $S = 0$  and  $R = 0$ , the component retains  $Q$ ,
  - ▶  $S = 1$  and  $R = 0$ , the component updates to  $Q = 1$ ,
  - ▶  $S = 0$  and  $R = 1$ , the component updates to  $Q = 0$ ,
  - ▶  $S = 1$  and  $R = 1$ , the component is meta-stable
- but
- ▶ when not enabled, the component is in storage mode so retains  $Q$ .

The behaviour of such a component is specified by

$$Q' = S \vee (\neg R \wedge Q),$$

and/or

$S$	$R$	Current		Next	
		$Q$	$\neg Q$	$Q'$	$\neg Q'$
0	0	0	1	0	1
0	0	1	0	1	0
0	1	?	?	0	1
1	0	?	?	1	0
1	1	?	?	?	?

#### Definition

A “D” latch/flip-flop component has one input  $D$ :

- ▶ when enabled, if
  - ▶  $D = 1$ , the component updates to  $Q = 1$ ,
  - ▶  $D = 0$ , the component updates to  $Q = 0$ ,
- but
- ▶ when not enabled, the component is in storage mode so retains  $Q$ .

The behaviour of such a component is specified by

$$Q' = D,$$

and/or

$D$	Current		Next	
	$Q$	$\neg Q$	$Q'$	$\neg Q'$
0	?	?	0	1
1	?	?	1	0

Notes:

## Part 2: latches, flip-flops, and register (3)

### Concepts

#### Definition

A “JK” latch/flip-flop component has two inputs  $J$  (or **set**) and  $K$  (or **reset**):

- ▶ when enabled, if
  - ▶  $J = 0$  and  $K = 0$ , the component retains  $Q$ ,
  - ▶  $J = 1$  and  $K = 0$ , the component updates to  $Q = 1$ ,
  - ▶  $J = 0$  and  $K = 1$ , the component updates to  $Q = 0$ ,
  - ▶  $J = 1$  and  $K = 1$ , the component toggles  $Q$ ,
- but
- ▶ when not enabled, the component is in storage mode so retains  $Q$ .

The behaviour of such a component is specified by

$$Q' = (J \wedge \neg Q) \vee (\neg K \wedge Q),$$

and/or

$J$	$K$	Current		Next	
		$Q$	$\neg Q$	$Q'$	$\neg Q'$
0	0	0	1	0	1
0	0	1	0	1	0
0	1	?	?	0	1
1	0	?	?	1	0
1	1	0	1	1	0
1	1	1	0	0	1

#### Definition

A “T” latch/flip-flop component has one input  $T$ :

- ▶ when enabled, if
  - ▶  $T = 0$ , the component retains  $Q$ ,
  - ▶  $T = 1$ , the component toggles  $Q$ ,
- but
- ▶ when not enabled, the component is in storage mode so retains  $Q$ .

The behaviour of such a component is specified by

$$Q' = (T \wedge \neg Q) \vee (\neg T \wedge Q) = T \oplus Q,$$

and/or

$T$	Current		Next	
	$Q$	$\neg Q$	$Q'$	$\neg Q'$
0	0	1	0	1
0	1	0	1	0
1	0	1	1	0
1	1	0	0	1

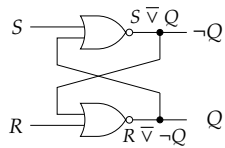
Notes:

## Part 2: latches, flip-flops, and register (4)

Design(s)

- **Problem #1:** we need an initial design for, e.g., an SR latch.
- **Solution:** use two *cross-coupled* NOR gates.

### Circuit



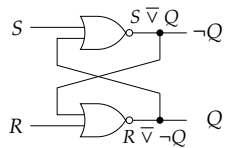
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## Part 2: latches, flip-flops, and register (4)

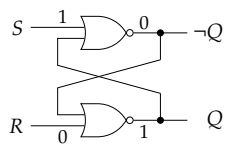
Design(s)

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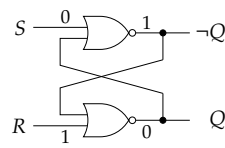
### Circuit



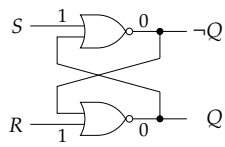
### Example ( $S = 1, R = 0, \checkmark$ )



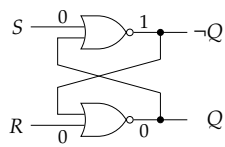
### Example ( $S = 0, R = 1, \checkmark$ )



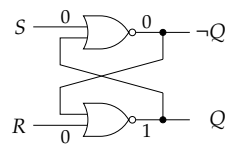
### Example ( $S = 1, R = 1, \times$ )



### Example ( $S = 0, R = 0, \checkmark$ )



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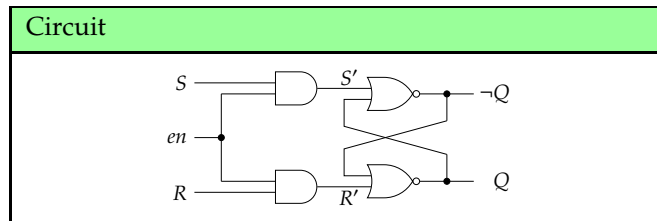
Notes:

## Part 2: latches, flip-flops, and register (5)

Design(s)

► **Problem #2:** we'd like to control when updates occur.

► **Solution:** *gate*  $S$  and  $R$ , i.e.,



noting that

- the same internal latch is evident, now with inputs  $S'$  and  $R'$ ,
- the external latch is such that

$$\begin{aligned} en = 0 &\Rightarrow S' = S \wedge en = S \wedge 0 = 0 \\ &\Rightarrow R' = R \wedge en = R \wedge 0 = 0 \end{aligned}$$

$$\begin{aligned} en = 1 &\Rightarrow S' = S \wedge en = S \wedge 1 = S \\ &\Rightarrow R' = R \wedge en = R \wedge 1 = R \end{aligned}$$

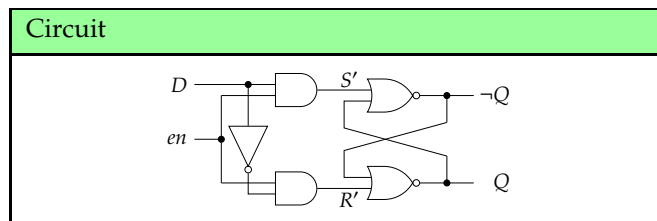
Notes:

## Part 2: latches, flip-flops, and register (6)

Design(s)

► **Problem #3:** we'd like to avoid the issue of meta-stability.

► **Solution:** force  $R = \neg S$  so we get either  $S = 0$  and  $R = 1$ , or  $S = 1$  and  $R = 0$ .



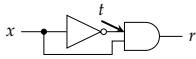
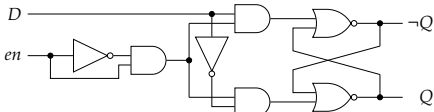
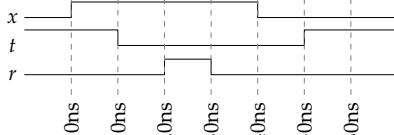
Notes:



## Part 2: latches, flip-flops, and register (7)

Design(s)

- **Problem #4:** we'd like an edge-triggered, rather than level-triggered design.
- **Solution #1:** "cheat" by approximation of an edge via a **pulse generator**.

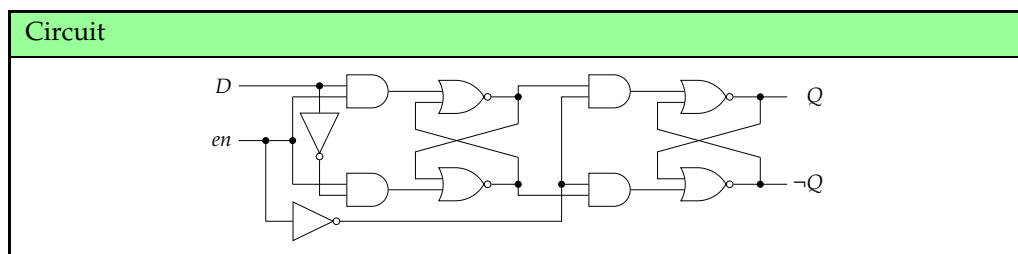
Circuit	Example
<p>The pulse generator component</p>  <p>is attached to the previous SR latch to give:</p> 	<p>Imagine we set the delay of</p> <ol style="list-style-type: none"> <li>1. a NOT gate to 10ns, and</li> <li>2. an AND gate to 20ns</li> </ol> <p>and then flip <math>en = 0</math> to <math>en = 1</math> and back again:</p>  <p>The result is a "pulse" matching the delay of a NOT gate that approximates an edge because it is so short.</p>

Notes:

## Part 2: latches, flip-flops, and register (8)

Design(s)

- **Problem #4:** we'd like an edge-triggered, rather than level-triggered design.
- **Solution #2:** adopt a **primary-secondary** organisation of *two* latches, i.e.,



where the idea is to split a clock cycle into to half-cycles:

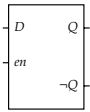
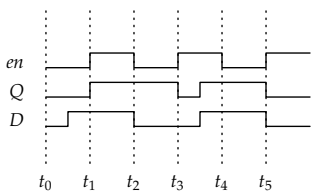
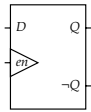
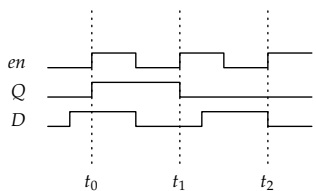
$en = 1 \Rightarrow$  **primary** latch is enabled  
 $en = 0 \Rightarrow$  **secondary** latch is enabled

meaning

1. *while*  $en = 1$ , i.e., positive level on  $en$ , primary latch stores input, and
2. *when*  $en = 0$ , i.e., negative edge on  $en$ , secondary latch stores output of primary latch, and hence we get edge-triggered behaviour.

Notes:

- Historically, the terms master and slave have often been used in place of primary and secondary. Per [8, Section 1.1], however, and despite some debate, the former are typically viewed as inappropriate now. We deliberately use the latter, therefore, noting that doing so may imply a need to translate the former when aligning with other literature.

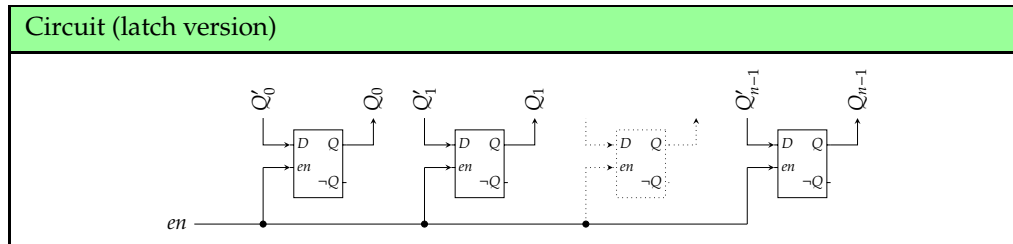
Definition	Definition
<p>► A <b>D-type latch</b> is described symbolically as</p>  <p>► The associated behaviour is, for example,</p>  <p>such that updates are level-triggered by <i>en</i>.</p>	<p>► A <b>D-type flip-flop</b> is described symbolically as</p>  <p>► The associated behaviour is, for example,</p>  <p>such that updates are edge-triggered by <i>en</i>.</p>

Notes:

## Part 2: latches, flip-flops, and register (10)

Aggregation, via registers

- **Concept:** we typically combine latches (resp. flip-flops) into **registers**, i.e.,



where

- there are  $n$  instances, so we can store an  $n$ -bit value: the  $i$ -th instance stores the  $i$ -th bit,
- access is conceptually straightforward:
  - read from register : use current value  $Q$
  - write to register : drive next value onto  $Q'$ , then trigger update via  $en$
- all instance share same  $en$ , so access to them is synchronised.

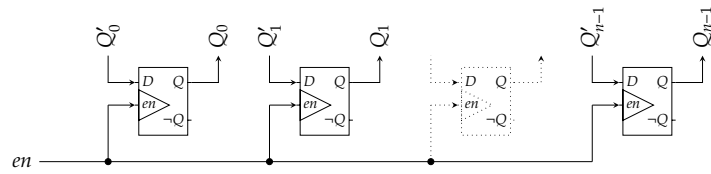
Notes:

## Part 2: latches, flip-flops, and register (10)

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### Circuit (flip-flop version)



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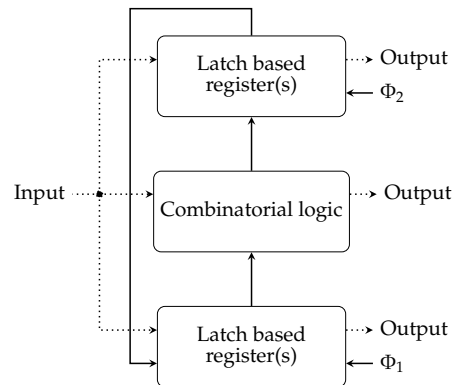
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Notes:

## Part 3: structure plus strategy (1)

Outcome: latch version, 2-phase clock

### Design (latch version)

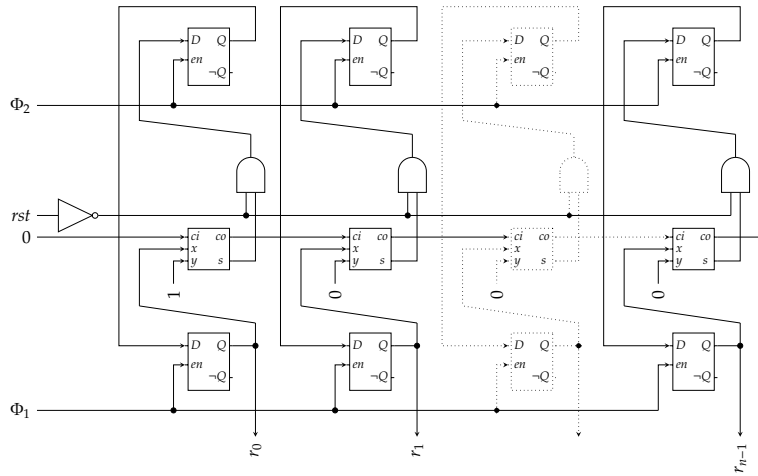


Notes:

### Part 3: structure plus strategy (2)

Outcome: latch version, 2-phase clock

#### Circuit (latch version)

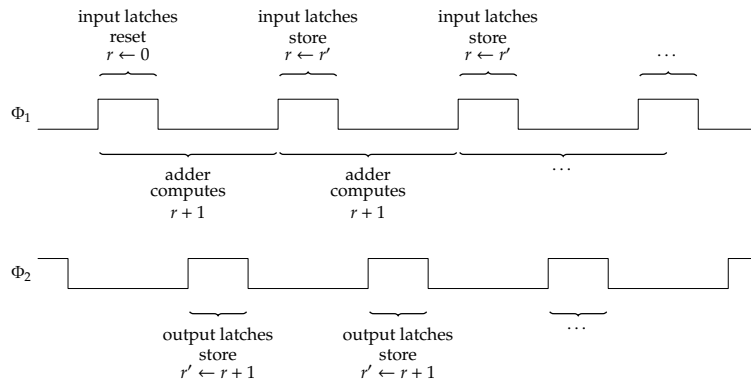


Notes:

### Part 3: structure plus strategy (3)

Outcome: latch version, 2-phase clock

#### Example (latch version)

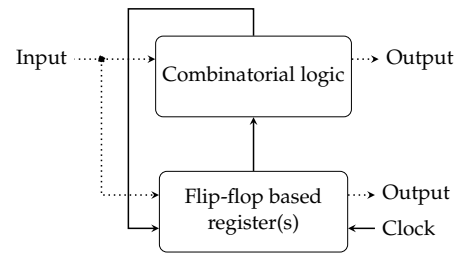


Notes:

### Part 3: structure plus strategy (4)

Outcome: flip-flop version, 1-phase clock

#### Design (flip-flop version)

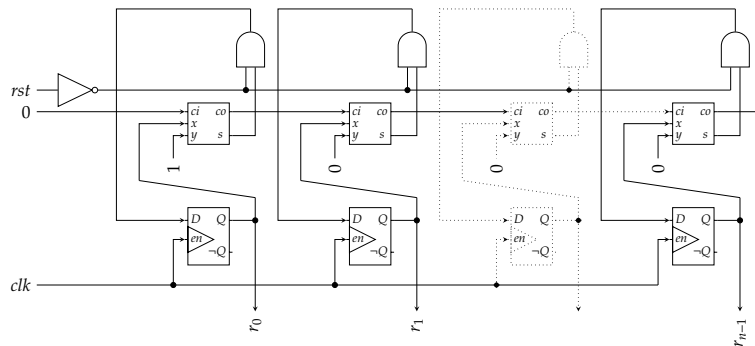


Notes:

### Part 3: structure plus strategy (5)

Outcome: flip-flop version, 1-phase clock

#### Circuit (flip-flop version)

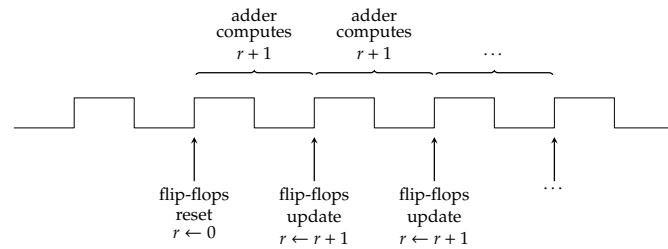


Notes:

## Part 3: structure plus strategy (6)

Outcome: flip-flop version, 1-phase clock

### Example (flip-flop version)



Notes:

## Conclusions

### ► Take away points:

1. Sequential logic design is typically hard(er) to understand (at first) than combinatorial logic design: invest some effort to address this now!
2. The main concept and challenge is *time*:
  - this goes beyond time in the sense of delay,
  - the goal is step-by-step, controlled (versus continuous, uncontrolled) computation,
  - we need to understand and manage, e.g., with parallelism and synchronisation.

Notes:

## Conclusions

### ► Take away points:

3. There is at least one higher-level design principle evident: we often see
  - a **data-path**, of computational and/or storage components, and
  - a **control-path**, that tells components in the data-path what to do and when to do it, although the counter control-path is (very) simple.
4. The next step is to formalise this, allowing solution of more complex problems, e.g., through more complex forms of control.

Notes:

## Additional Reading

- *Wikipedia: Sequential logic*. URL: [https://en.wikipedia.org/wiki/Sequential\\_logic](https://en.wikipedia.org/wiki/Sequential_logic).
- D. Page. “Chapter 2: Basics of digital logic”. In: *A Practical Introduction to Computer Architecture*. 1st ed. Springer, 2009.
- W. Stallings. “Chapter 11: Digital logic”. In: *Computer Organisation and Architecture*. 9th ed. Prentice Hall, 2013.
- A.S. Tanenbaum and T. Austin. “Section 3.2.2: Clocks”. In: *Structured Computer Organisation*. 6th ed. Prentice Hall, 2012.
- A.S. Tanenbaum and T. Austin. “Section 3.3.4: Latches”. In: *Structured Computer Organisation*. 6th ed. Prentice Hall, 2012.
- A.S. Tanenbaum and T. Austin. “Section 3.3.4: Flip-flops”. In: *Structured Computer Organisation*. 6th ed. Prentice Hall, 2012.
- A.S. Tanenbaum and T. Austin. “Section 3.3.4: Registers”. In: *Structured Computer Organisation*. 6th ed. Prentice Hall, 2012.

Notes:

## References

- [1] [Wikipedia: Sequential logic](#). URL: [https://en.wikipedia.org/wiki/Sequential\\_logic](https://en.wikipedia.org/wiki/Sequential_logic) (see p. 59).
- [2] D. Page. “Chapter 2: Basics of digital logic”. In: *A Practical Introduction to Computer Architecture*. 1st ed. Springer, 2009 (see p. 59).
- [3] W. Stallings. “Chapter 11: Digital logic”. In: *Computer Organisation and Architecture*. 9th ed. Prentice Hall, 2013 (see p. 59).
- [4] A.S. Tanenbaum and T. Austin. “Section 3.2.2: Clocks”. In: *Structured Computer Organisation*. 6th ed. Prentice Hall, 2012 (see p. 59).
- [5] A.S. Tanenbaum and T. Austin. “Section 3.3.4: Flip-flops”. In: *Structured Computer Organisation*. 6th ed. Prentice Hall, 2012 (see p. 59).
- [6] A.S. Tanenbaum and T. Austin. “Section 3.3.4: Latches”. In: *Structured Computer Organisation*. 6th ed. Prentice Hall, 2012 (see p. 59).
- [7] A.S. Tanenbaum and T. Austin. “Section 3.3.4: Registers”. In: *Structured Computer Organisation*. 6th ed. Prentice Hall, 2012 (see p. 59).
- [8] M. Knodel and N. ten Oever. *Terminology, Power and Oppressive Language*. Internet Engineering Task Force (IETF) Internet Draft. 2018. URL: <https://tools.ietf.org/id/draft-knodel-terminology-00.html> (see p. 36).

Notes: