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  1. communication media and signals,
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  3. multiplexing, and
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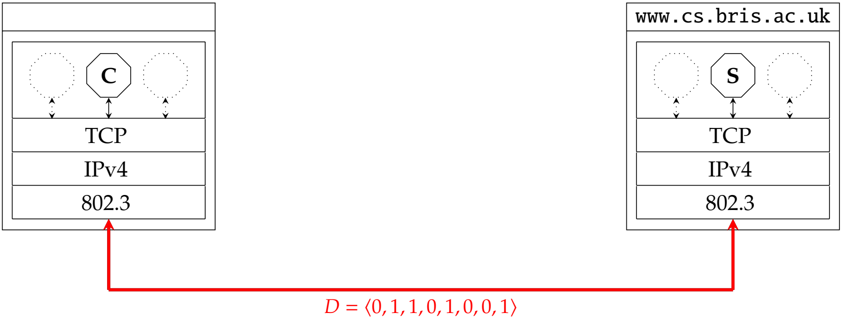
  st. we can transmit (unstructured) **bit-sequences** along a physical connection between two end-points.



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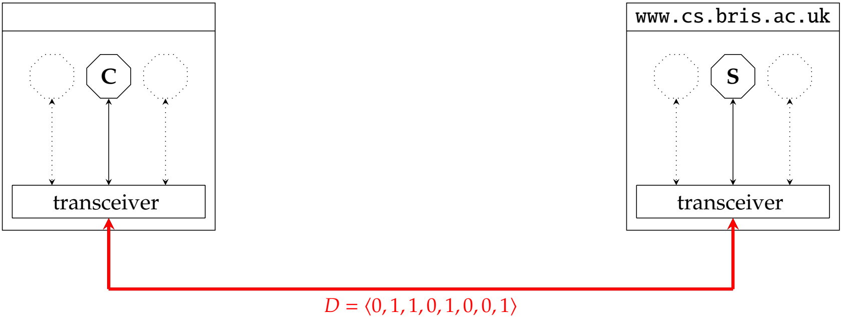

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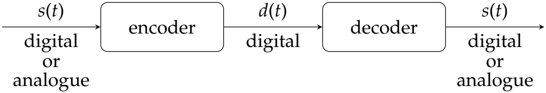
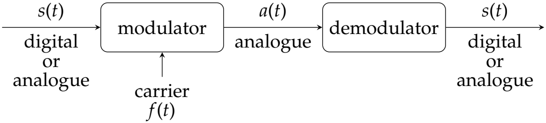
  st. we can transmit (unstructured) **bit-sequences** along a physical connection between two end-points.

- **Idea**:
  - we have some digital input (i.e., our data), so can
    1. directly **encode** it, i.e.,



       via a digital signalling scheme, or
    2. use it to **modulate** a **carrier signal**, i.e.,



       via an analogue signalling scheme

    to produce an (digital or analogue) output signal,
  - so can then transmit that signal along a communication medium (e.g., a wire), and
  - the resulting behaviour has a clear theoretical basis.

Definition (**sinusoid**)

The sinusoidal function

$$s(t) = A \cdot \sin(2\pi \cdot f \cdot t + \varphi)$$

is periodic, and parameterised by

1. an **amplitude** A (which is the maximum deviation of $s(t)$ from 0),
2. a **frequency** f (which is inversely proportional to the period, which is normally termed the **wavelength** λ), and
3. a **phase** (or offset) φ (which basically dictates where in the cycle the wave is at time $t = 0$).

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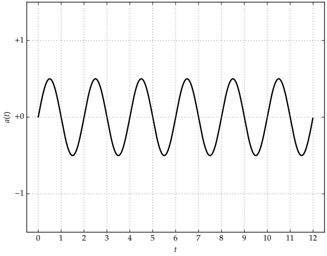
By evaluating over a time period (i.e., over a range of t), such a wave can be visualised as a **waveform**, e.g.,



where $A = 0.5$, $f = 0.5$, $\varphi = 0$.

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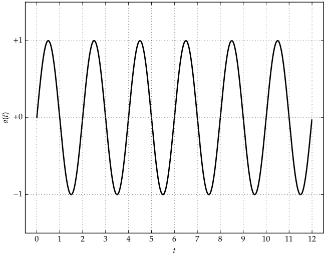

where $A = 1.0$, $f = 0.5$, $\varphi = 0$.

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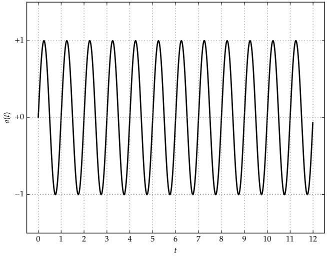

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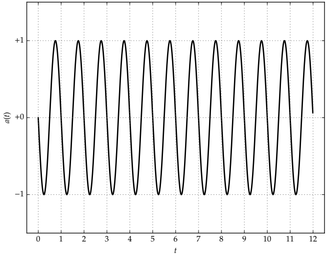


where $A = 1.0, f = 1.0, \varphi = \pi$.

"Communication Theory in 10 minutes" (3)

Definition (Fourier analysis [4])

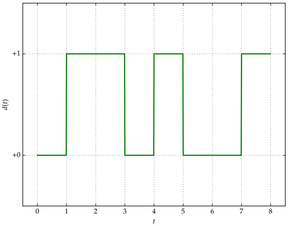
Fourier analysis allows us to represent a signal as an (infinite) sum of sinusoids:

$$s(t) \sim \frac{a_0}{2} + \sum_{n=1}^{\infty} a_n \cdot \cos(2\pi \cdot f \cdot t \cdot n) + b_n \cdot \sin(2\pi \cdot f \cdot t \cdot n)$$

The resulting **Fourier series** (or **Fourier expansion**) $s(t)$ typically makes use of **Fourier coefficients** a_n and b_n for $1 \leq n < N$ wrt. some (finite) bound N.

"Communication Theory in 10 minutes" (4)

- Eh?!



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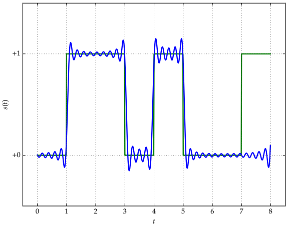

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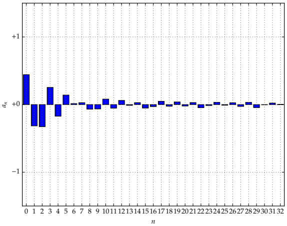

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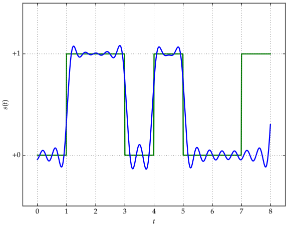

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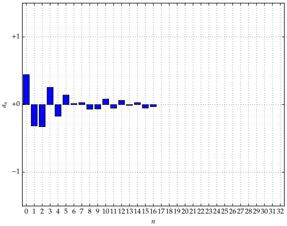

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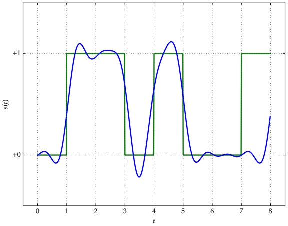

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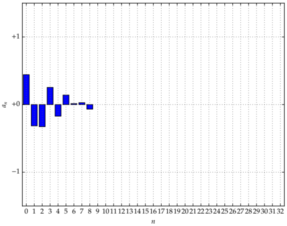

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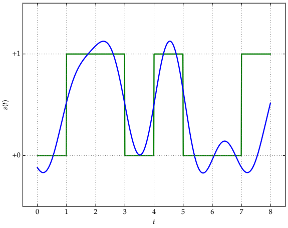

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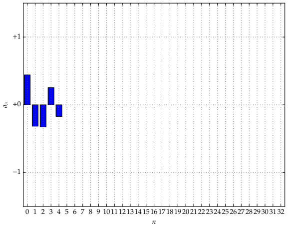

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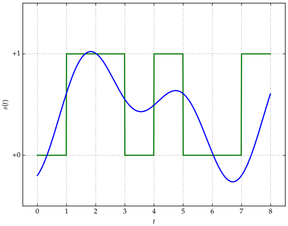

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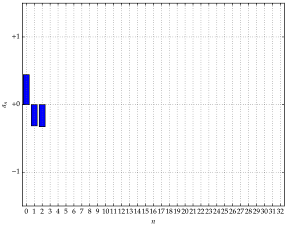

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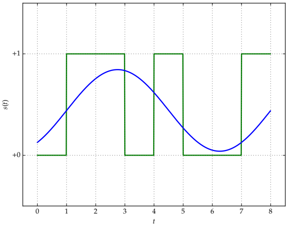

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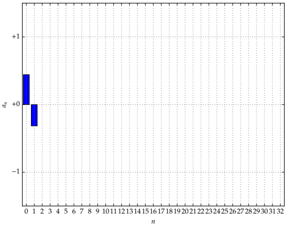

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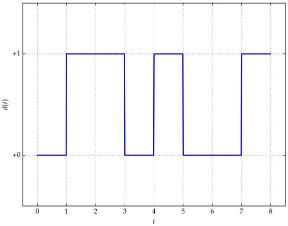

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- *but*, when transmitted, the signal will still be
  1. **delayed**, since it takes time to propagate,
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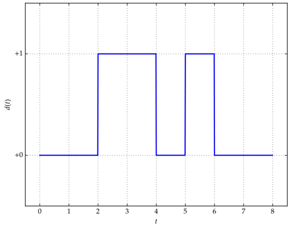

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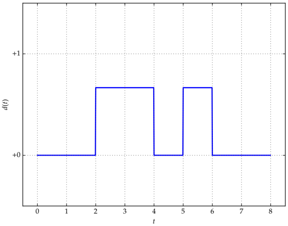

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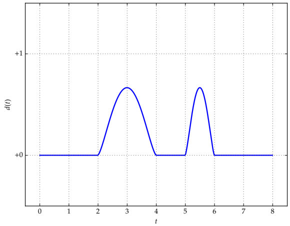

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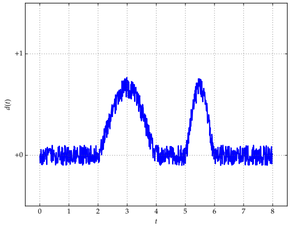

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Definition (**signalling levels**)

When sampled at a given instance in time, a signal will take one of l **signalling levels**; this means each **symbol** transmitted will take one of l values. Note that $l > 2$ implies the ability to transmit *more* than 1 bit of information per symbol.

Definition (**modulation rate**)

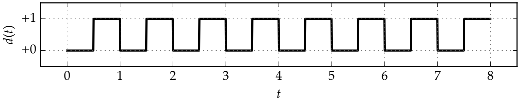
The **modulation rate** measures how quickly (i.e., how often per unit of time) the channel can change (or transition, which may be termed a **signalling event**) between signalling levels; this of course determines the (minimum) **symbol period**.

Encoding/Modulation (1) – Digital signalling

Original data

0 1 1 0 1 0 0 1

Clock signal



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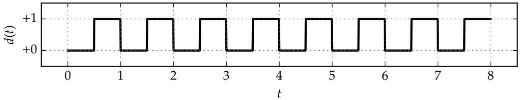
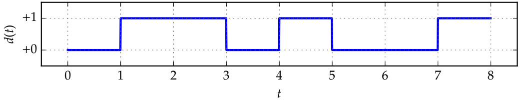


Non-Return to Zero (NRZ)



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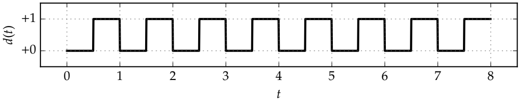
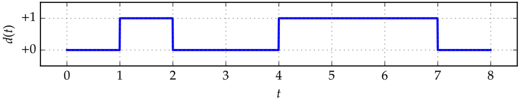
Original data

0 1 1 0 1 0 0 1

Clock signal



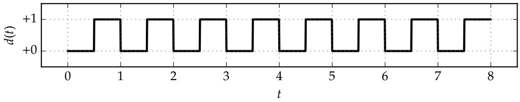
Non-Return to Zero Inverted (NRZ-I)



Original data

0 1 1 0 1 0 0 1

Clock signal



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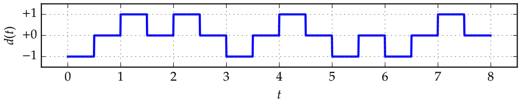
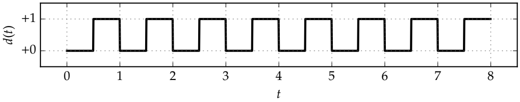


Encoding/Modulation (1) – Digital signalling

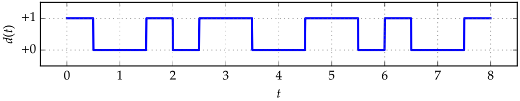
Original data

0 1 1 0 1 0 0 1

Clock signal



Manchester (per 802.3)



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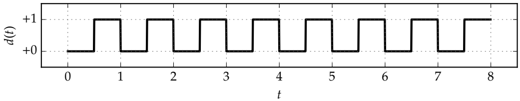
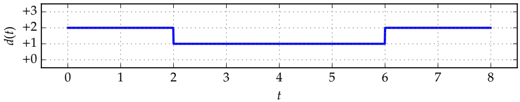


***l*-ary (for $l = 4$)**

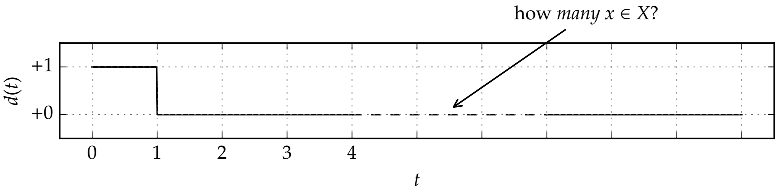


Encoding/Modulation (2) – Digital signalling

- ... or, to summarise, we have something like the following

Scheme	Signalling levels	Modulation rate	Self clocked?	Differential ?	Runs of $x \in X$
NRZ	2	r	×	×	$X = \{0, 1\}$
NRZ-I	2	r	×	✓	$X = \{0\}$
RZ	2(ish)	$r \cdot 2$	✓	×	$X = \emptyset$
Manchester	2	$r \cdot 2$	✓	×	$X = \emptyset$
l-ary	l	$r / \log_2(l)$	×	×	$X = \{0, 1, \ldots, n-1\}$

where the last column suggests a problem, i.e.,



Encoding/Modulation (3) – Digital signalling

- (A) solution:
  1. *pre*-encode the data, e.g., by using a **block code** such as **4B/5B** where

4-bit data word	5-bit code word
0000	11110
0001	01001
0010	10100
0011	10101
0100	01010
0101	01011
0110	01110
0111	01111
1000	10010
1001	10011
1010	10110
1011	10111
1100	11010
1101	11011
1110	11100
1111	11101

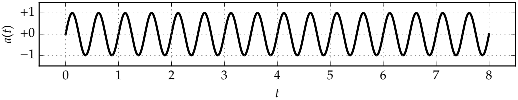
  2. the combination of say 4B/5B plus NRZ-I means
     - there is never a long sequence of transmitted 0 or 1, *and*
     - the overhead is *lower* than using alternatives such as Manchester.

Encoding/Modulation (4) – Analogue signalling

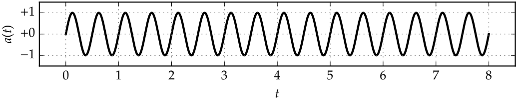
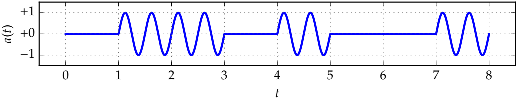
Original data

0 1 1 0 1 0 0 1

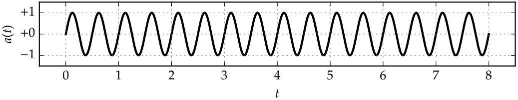
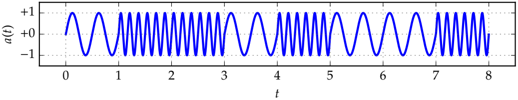
Carrier signal



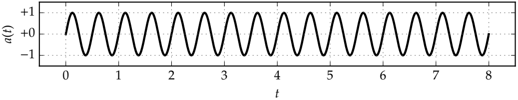
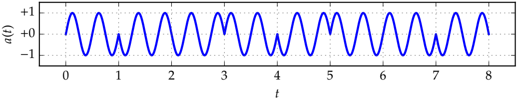
Encoding/Modulation (4) – Analogue signalling

Original data	0 1 1 0 1 0 0 1
Carrier signal	
Amplitude-Shift Keying (ASK)	

Encoding/Modulation (4) – Analogue signalling

Original data	0 1 1 0 1 0 0 1
Carrier signal	
Frequency-Shift Keying (FSK)	

Encoding/Modulation (4) – Analogue signalling

Original data	0 1 1 0 1 0 0 1
Carrier signal	
Phase-Shift Keying (PSK)	

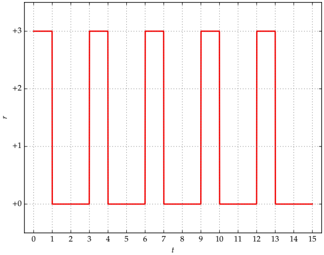
Multiplexing (1)

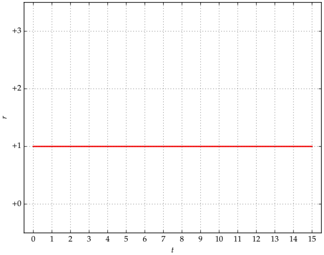
- Problem: what if we have 1 communication medium, and m streams of data (each of n symbols say)?
- (A) solution: statically **(de)multiplex** the streams, via
  1. **Time-Division Multiplexing (TDM)**, st. time is divided into "slots" and then allocated on a round-robin basis to the streams, or
  2. **Frequency-Division Multiplexing (FDM)**, where each stream is "shifted" into a different range of frequencies.

  or, from the perspective of a given stream ...

Multiplexing (2)

- ... we can visualise utilisation as

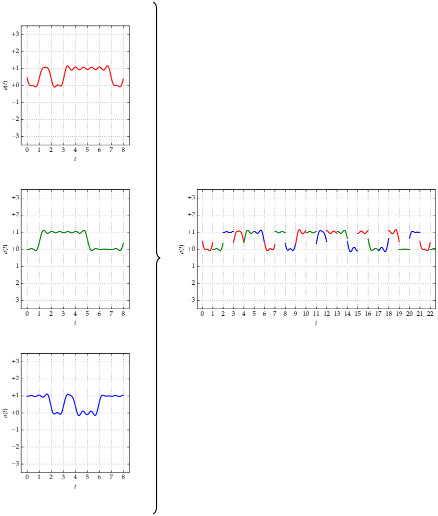




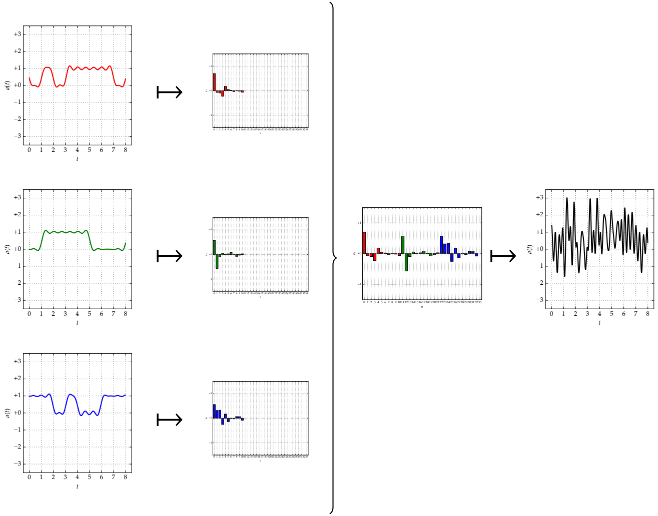
st. the stream either

1. has access to *all* of the available bandwidth, but for *part* of the time, or
2. has access to *part* of the available bandwidth, but for *all* of the time.

Multiplexing (3) – TDM



Multiplexing (4) – FDM



Metrics (2)

Definition (**bandwidth**)

The **bandwidth** of a communication channel is the number of symbols which can be transmitted per unit of time; this is sometimes referred to as the **channel capacity**, and often measured in bits per second (which is then the **bit rate**).

It is common to contrast total available bandwidth, with that achievable in practice; the latter is termed **throughput**, st.

$$\text{bandwidth} \geq \text{throughput} + \text{overhead}.$$

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Definition (**latency**)

The **latency** of a connection relates to the (total) time required to transmit data between two end-points (e.g., between $\mathcal{H}_0$ and $\mathcal{H}_1$). This is typically expressed as $n/r + d$, where

- n/r is the **transmission delay**, and
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given n symbols and a bandwidth of r symbols per unit of time. Note that

- **One-Way Delay (OWD)** measures the latency of $\mathcal{H}_0$ transmitting data to $\mathcal{H}_1$, whereas
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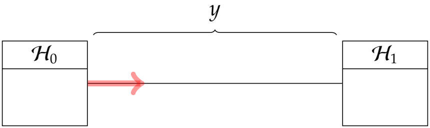

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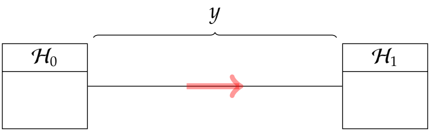

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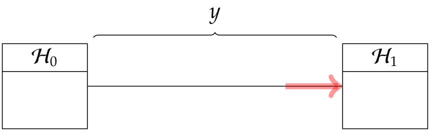

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st. latency $=$ $x + y$ $=$ transmission delay + propagation delay.

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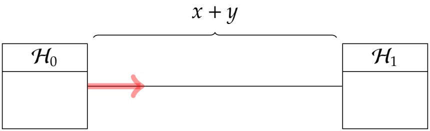

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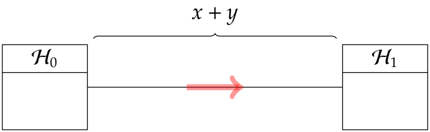

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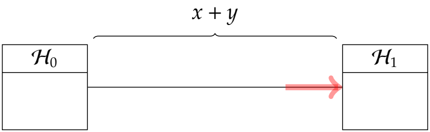

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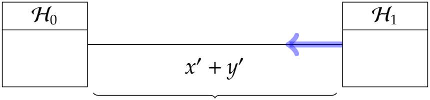

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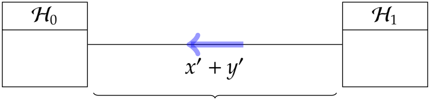

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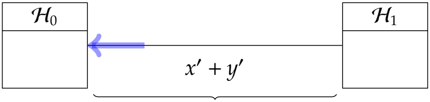

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i.e.,

st. $\text{RTT} = (x + y) + (x' + y') \geq 2 \cdot \text{OWD}.$

Metrics (2)

Definition (**bandwidth-latency product**)

Imagine that a given channel is a pipe, whose diameter is defined by bandwidth and length by latency. The "volume" of the pipe is termed the **bandwidth-latency product** (or **bandwidth-delay product**), and captures the amount of data "in-flight".

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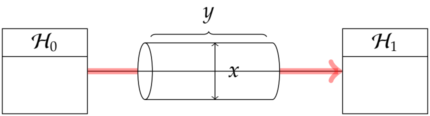

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st. bandwidth-latency product $= x \cdot y =$ bandwidth $\cdot$ latency

Conclusions

- Take away points:
  - Digital and analogue signal processing is a *big* topic; this is a light-weight introduction only!
  - There are *many* of possible ways to address the initial (fairly simple) goal ...
  - ... on one hand this is great (because we can match a choice to our needs); on the other, it's not so great (since making a *good* choice is harder).
  - Keep in mind that
    1. a given approach is often underpinned by theory, but
    2. choices are often made with lower-level, Engineering requirements in mind,
    3. we can only make *good* choices by understanding how the channel is used.

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