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Data Convertor Ⅱ
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S38-7

Integral-type Time-to-Digital Converter

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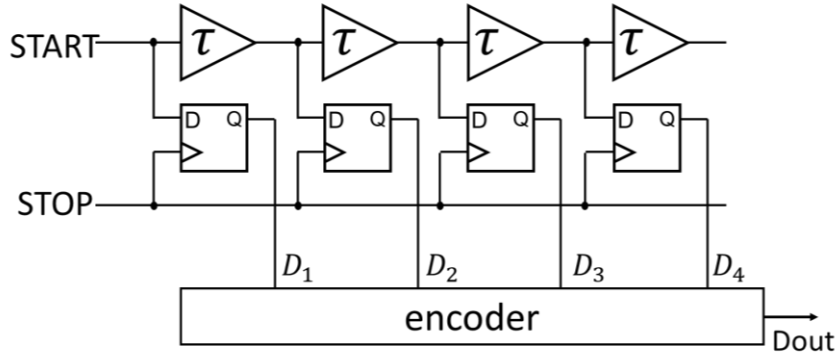
Motivation

TDC Architectures with NO delay lines

- for higher time resolution
- to avoid PVT variations of delay lines:
  - Process
  - Voltage
  - Temperature



Conventional TDC

Outline

- Introduction
- Proposed TDC Architecture and Operation
- Highly Efficient Data Acquisition Condition
- Jitter Effects
- Summary

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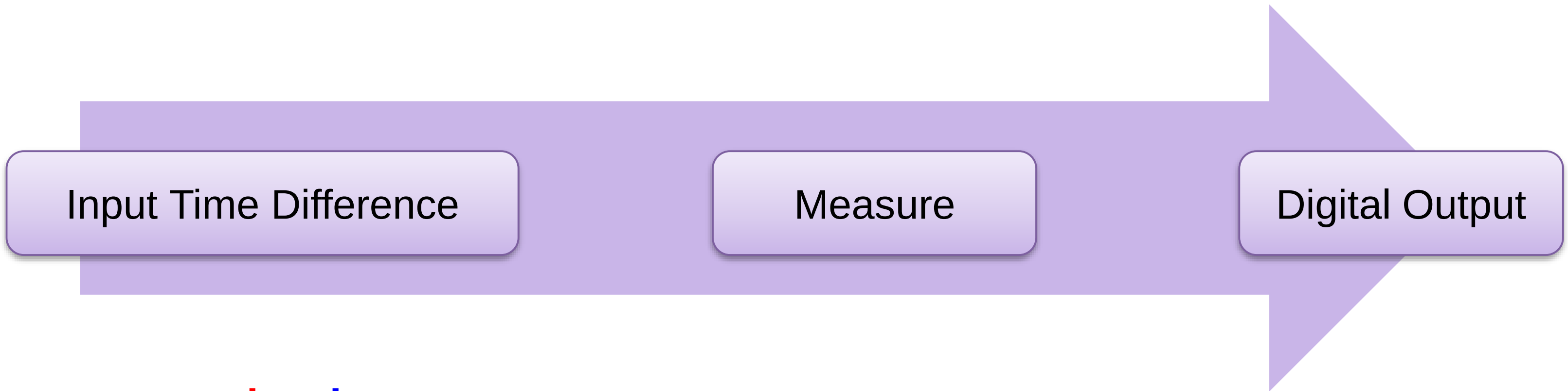
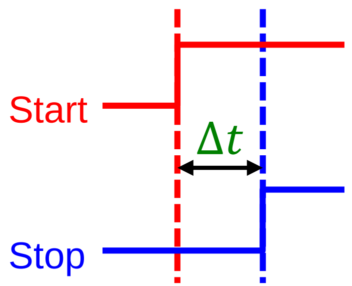
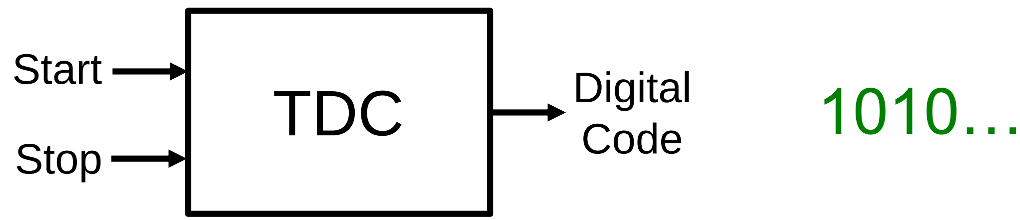
Time-to-Digital Converter

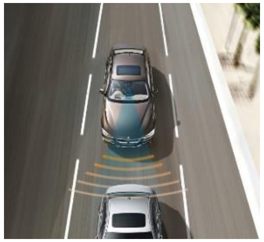




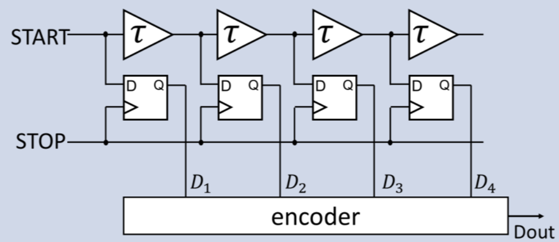
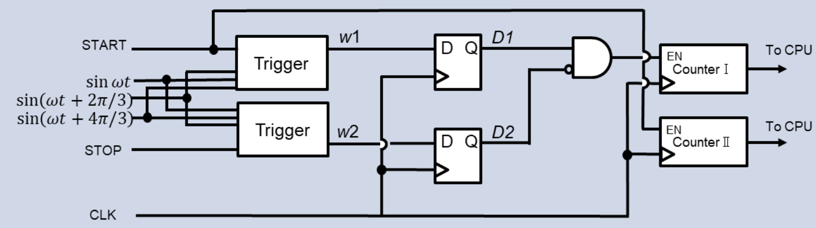


Time-to-Digital Converter (TDC) :

measures timing difference between two input signals as a digital code



Comparison

	Conventional TDC	Proposed TDC
Architecture		
Delay Line	YES	NO
PVT Variation	Large	Small
Self Calibration	Required	Not Required
Time Resolution	Low	High
Measuring Time	Short	Long
Analog Circuit	NO	YES

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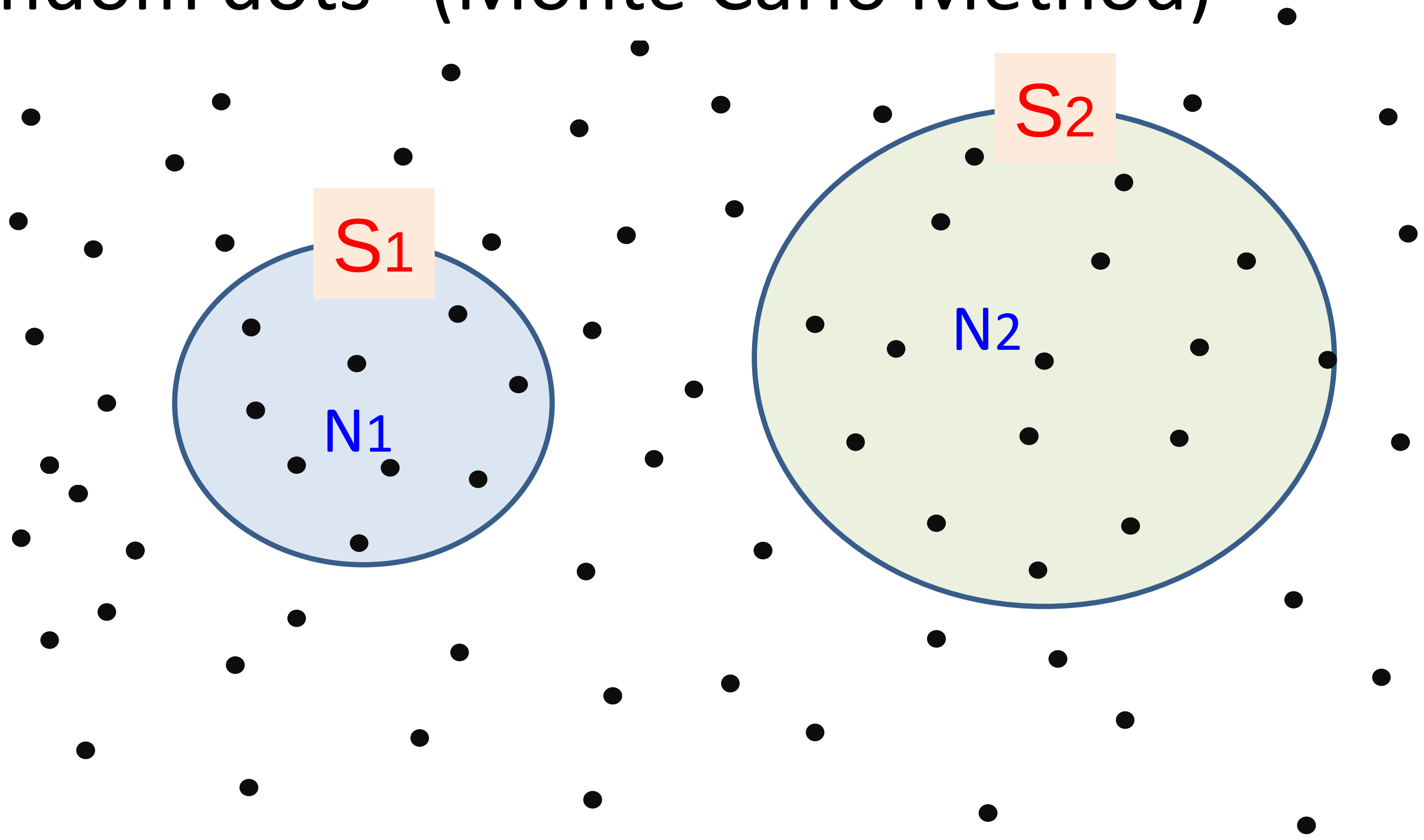
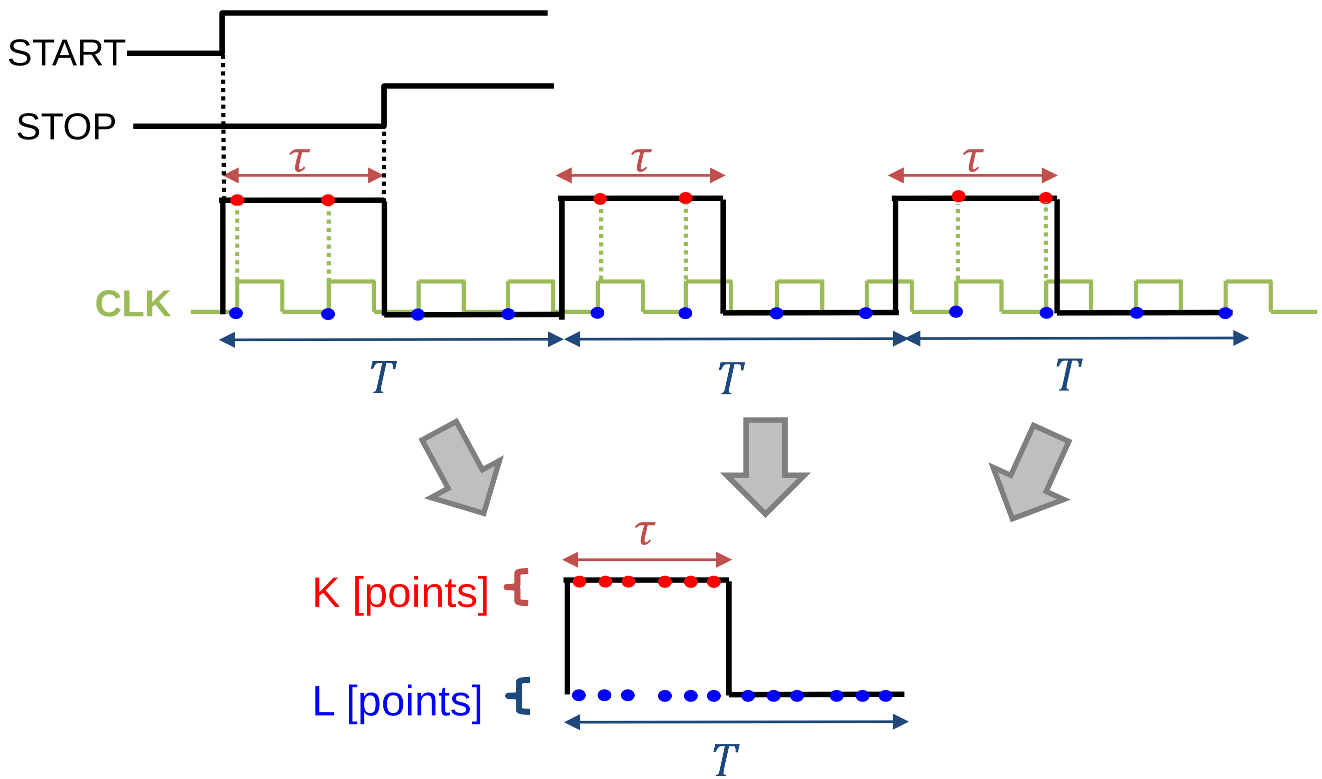
Probabilistic Measurement

Random dots (Monte Carlo Method)



# of dots ratio $\frac{N_1}{N_2}$ ⇒ Area ratio $\frac{S_1}{S_2}$

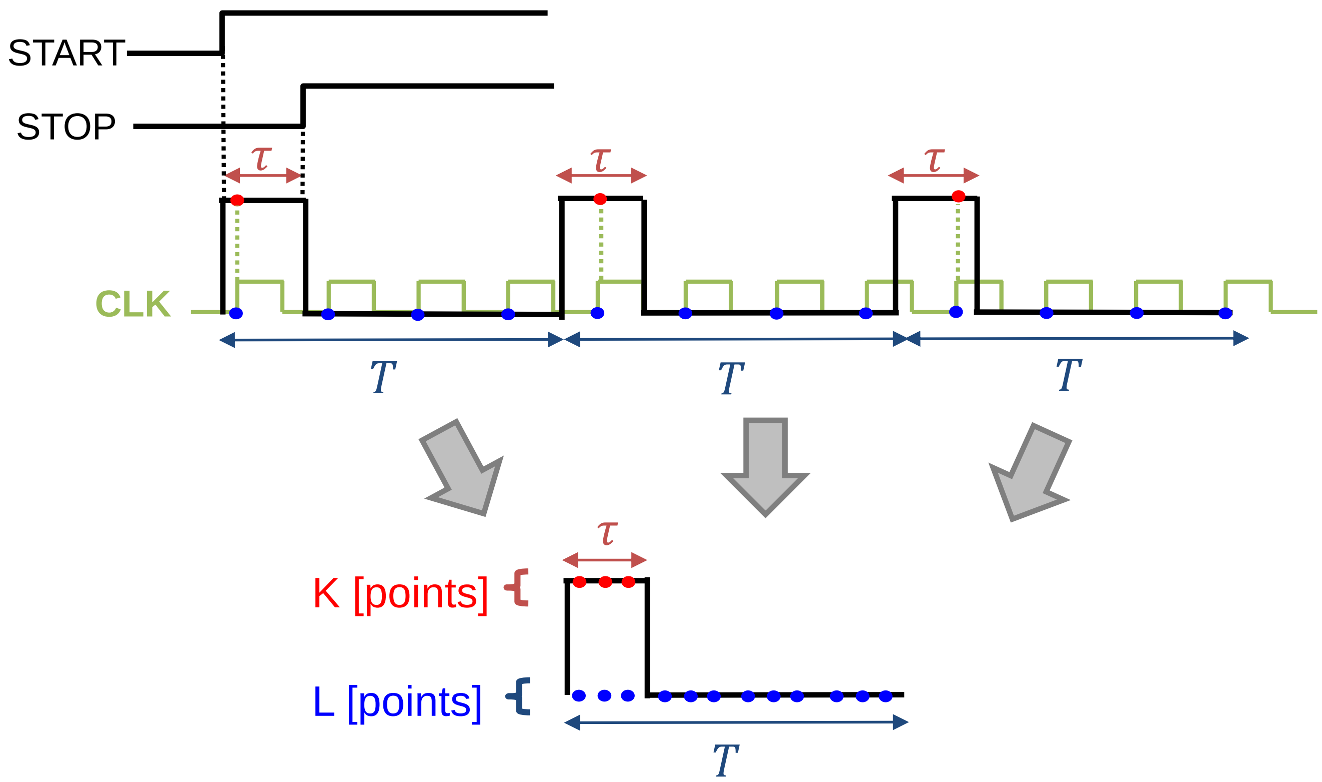
Proposed TDC Principle (1/3)



Sampling a square wave with **input time difference τ / reference period T** duty cycle

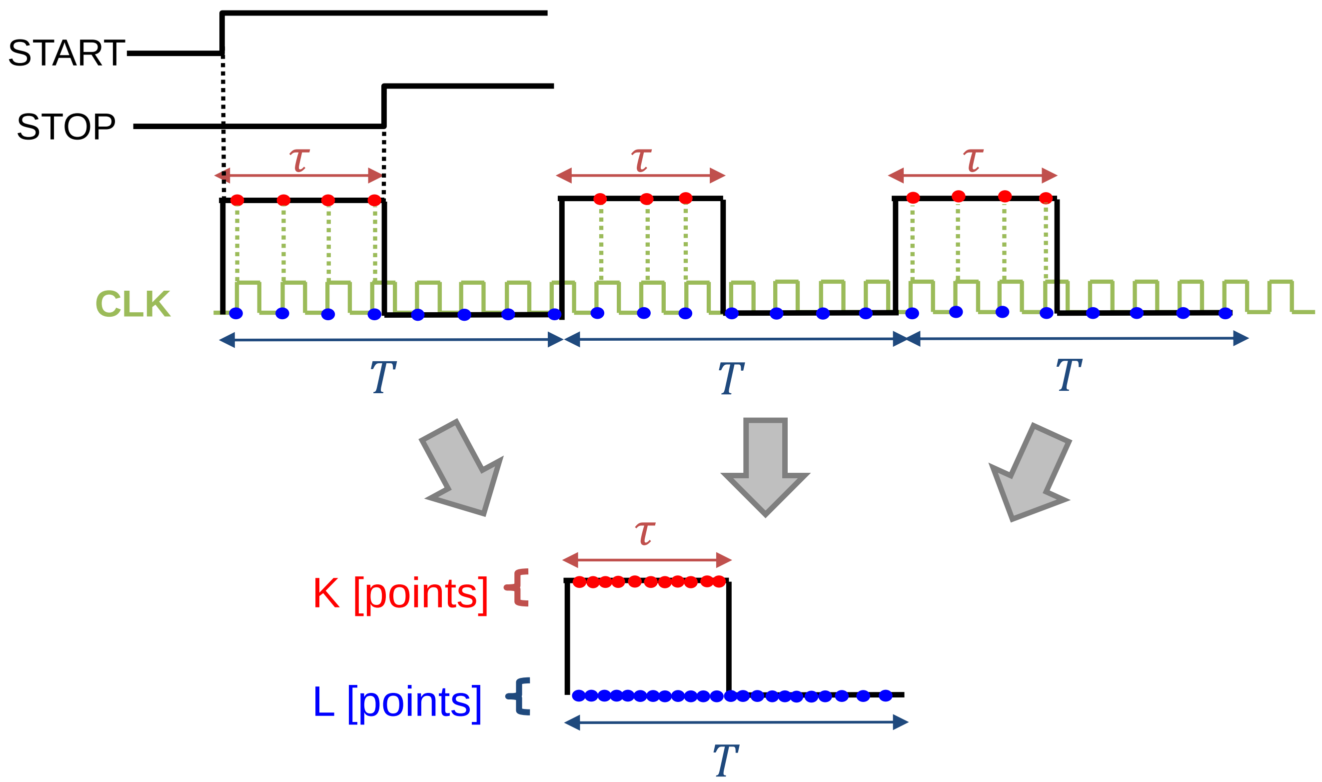
$$\lim_{L\to\infty}\frac{K}{L}=\frac{\tau}{T}$$

Proposed TDC Principle (2/3)



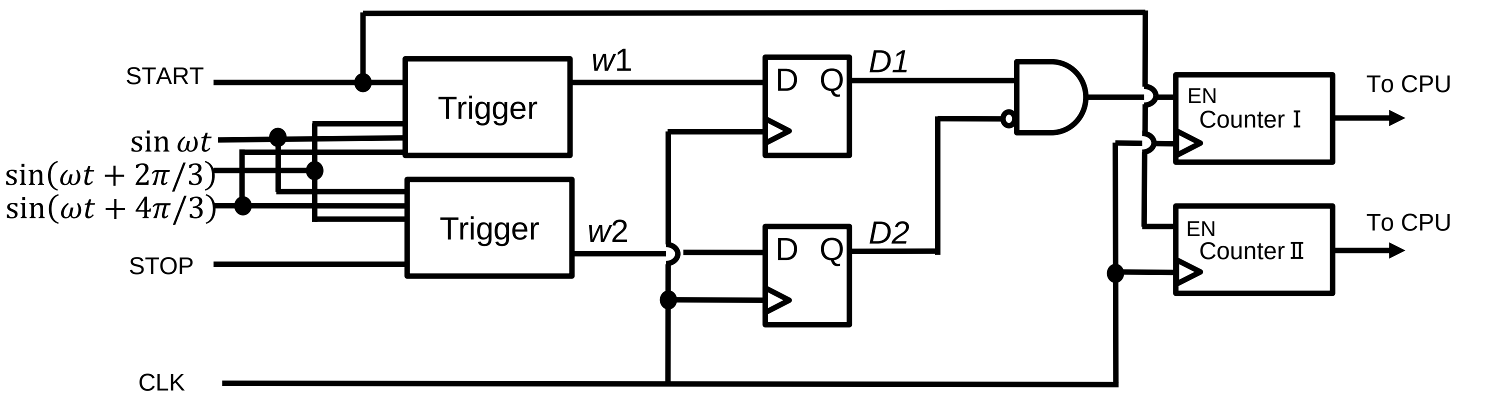
Square wave duty cycle depends on input time difference τ

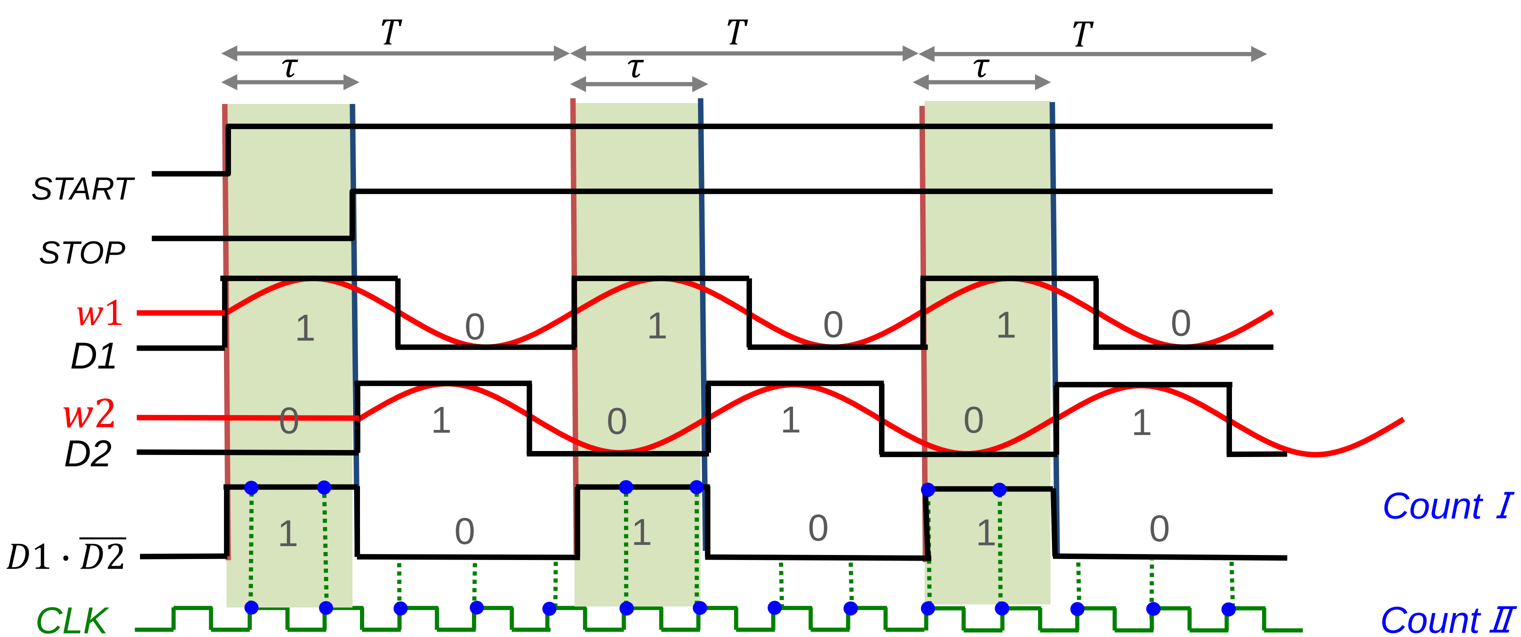
Proposed TDC Principle (3/3)



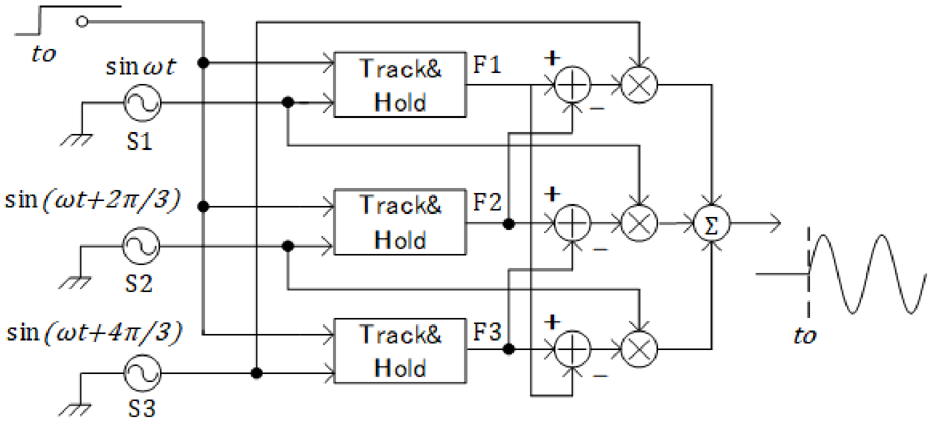
Acquiring more data improves time resolution

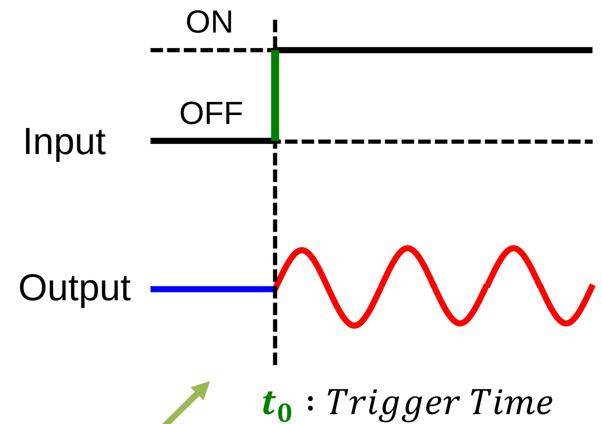
Proposed TDC Architecture





Oscilloscope-Trigger Circuit (1/2)

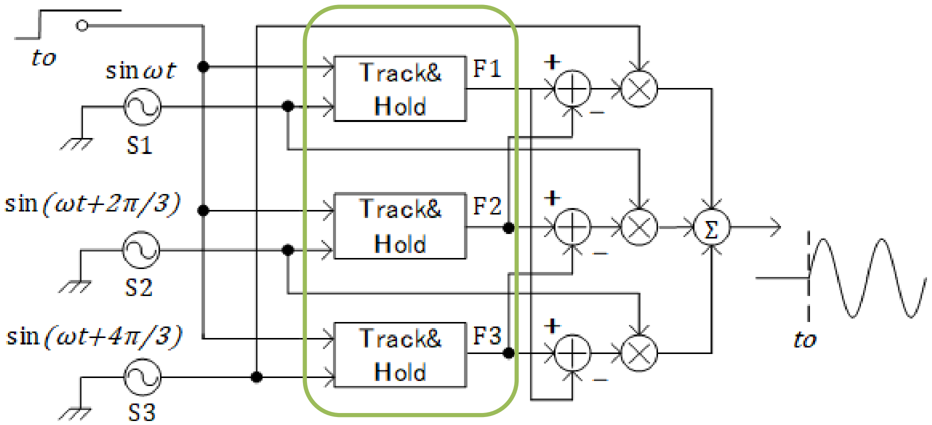


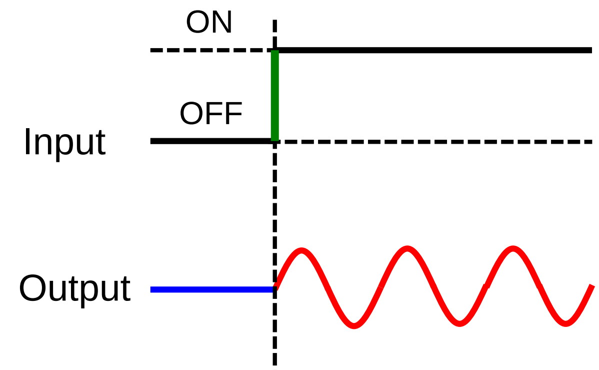


Output starts to oscillate at **rising edge timing of input** from **phase 0**

[1] M. Nelson (Tektronics)
"A New Technique for Low-Jitter Measurements Using Equivalent-Time Sampling Oscilloscope"
Automatic RF Techniques Group 56th Measurement (Dec. 2000)

Oscilloscope-Trigger Circuit (2/2)





t_0 : *Trigger Time*

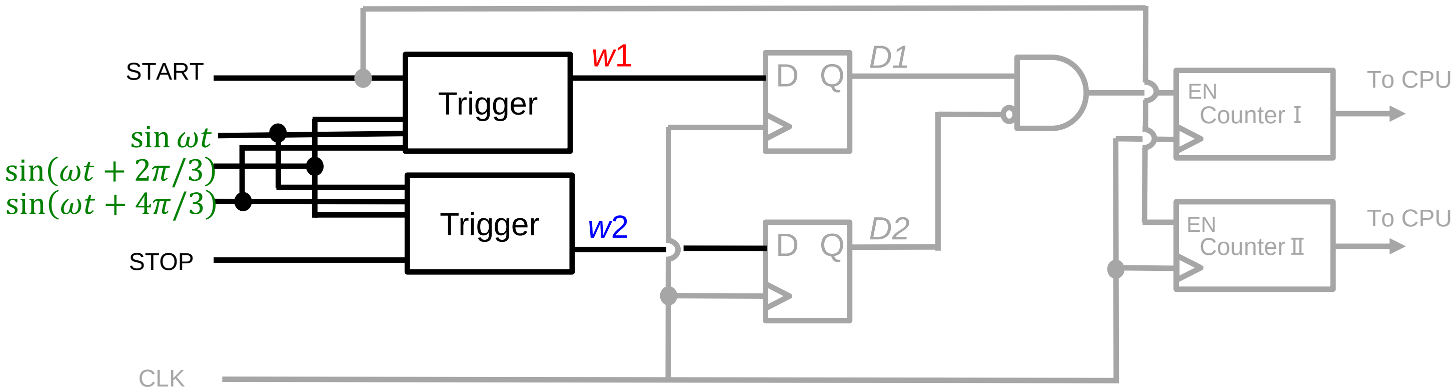
Track mode:

$$V_{out} = \sin(\omega t + 4\pi/3)\{\sin \omega t - \sin(\omega t + 2\pi/3) \\ + \sin \omega t\,\{\sin(\omega t + 2\pi/3) + \sin(\omega t + 4\pi/3)\} \\ + \sin(\omega t + 2\pi/3)\{\sin(\omega t + 2\pi/3) + \sin(\omega t + 4\pi/3)\} = \mathbf{0}$$

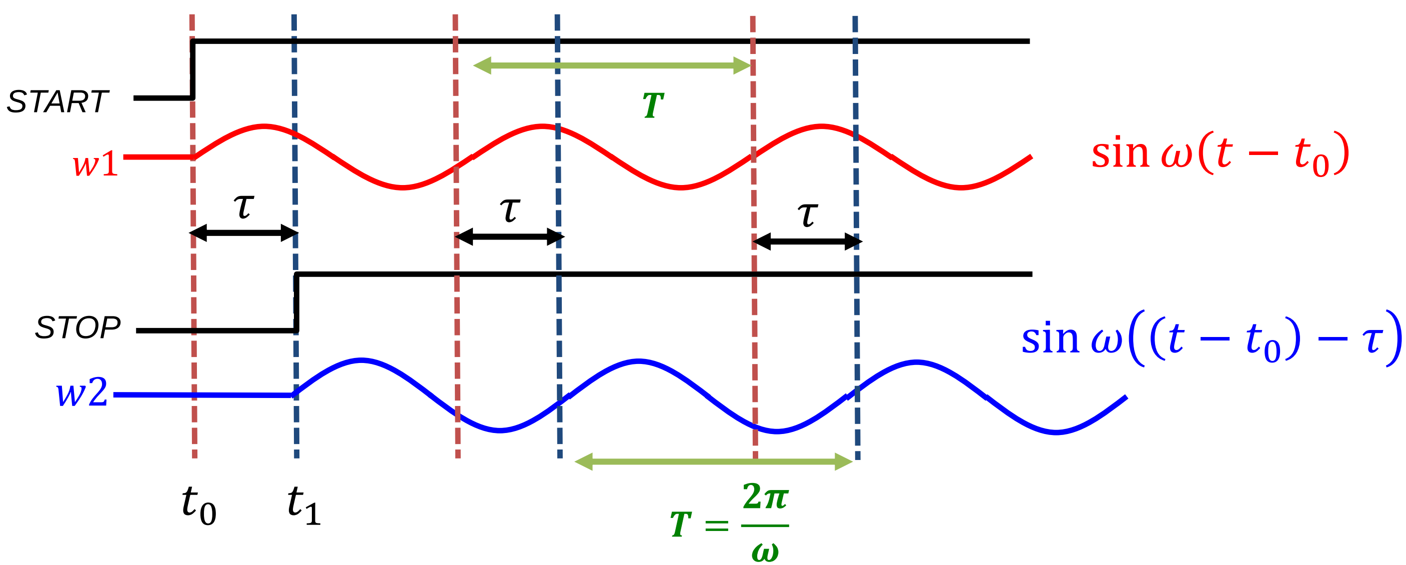
Hold mode:

$$V_{out} = \sin(\omega t + 4\pi/3)\{\sin \omega t_0 - \sin(\omega t_0 + 2\pi/3) \\ + \sin \omega t\,\{\sin(\omega t_0 + 2\pi/3) + \sin(\omega t_0 + 4\pi/3)\} \\ + \sin(\omega t + 2\pi/3)\{\sin(\omega t_0 + 2\pi/3) + \sin(\omega t_0 + 4\pi/3)\} \\ = \boldsymbol{\left(\left(3\sqrt{3}\right)/2\right)\sin(\omega\,(t - t_0))}$$

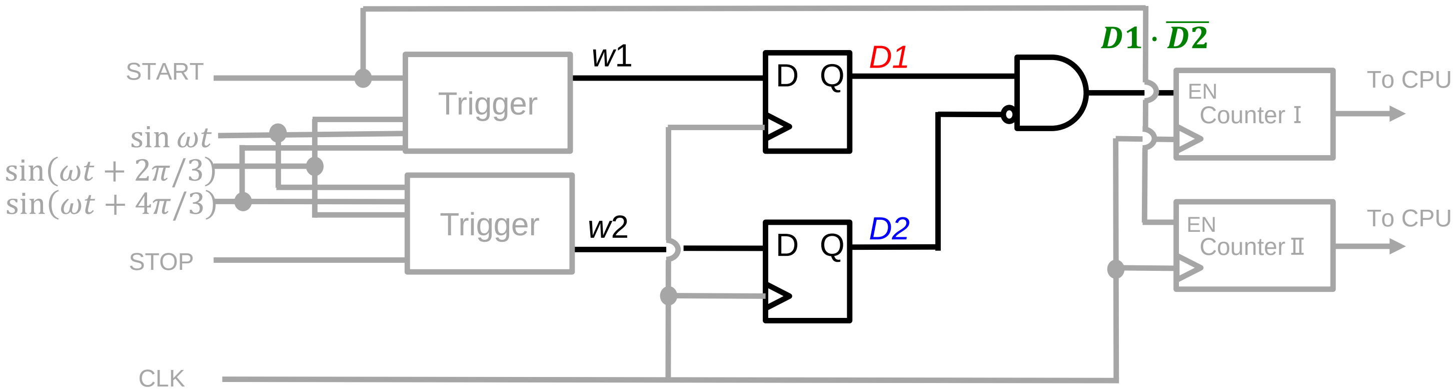
Proposed TDC Operation (1/3)



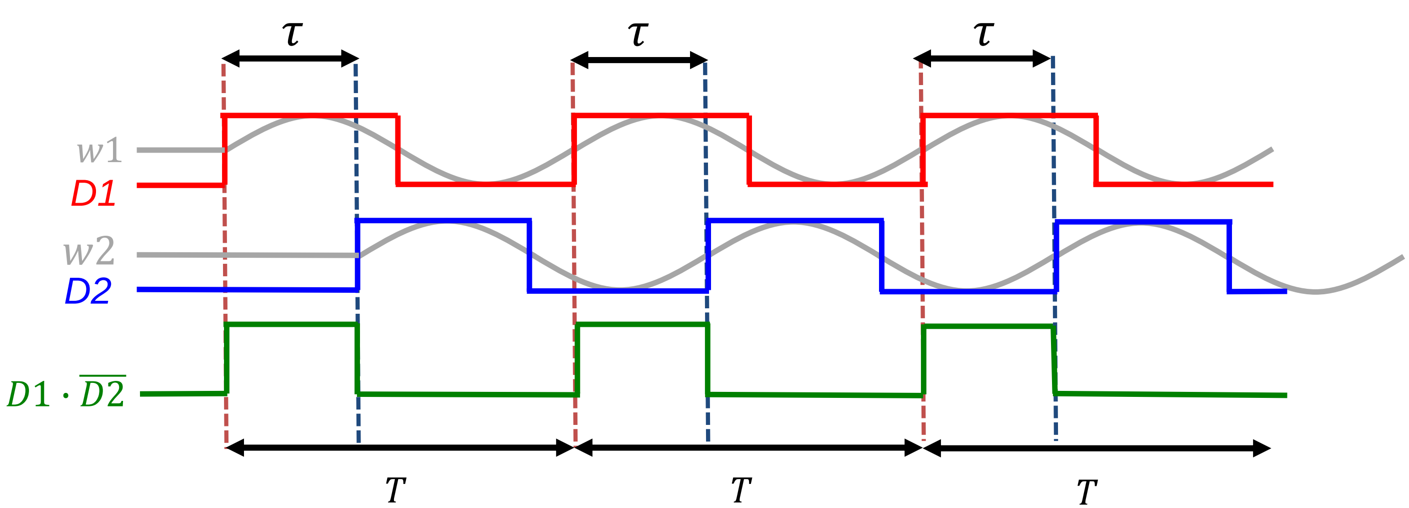
STEP1: Holding the input time difference τ as phase difference



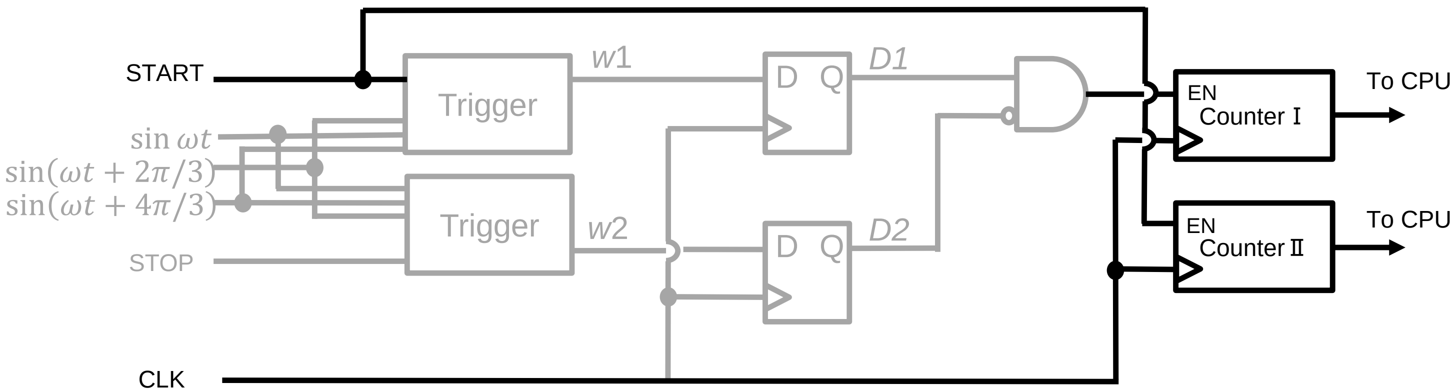
Proposed TDC Operation (2/3)



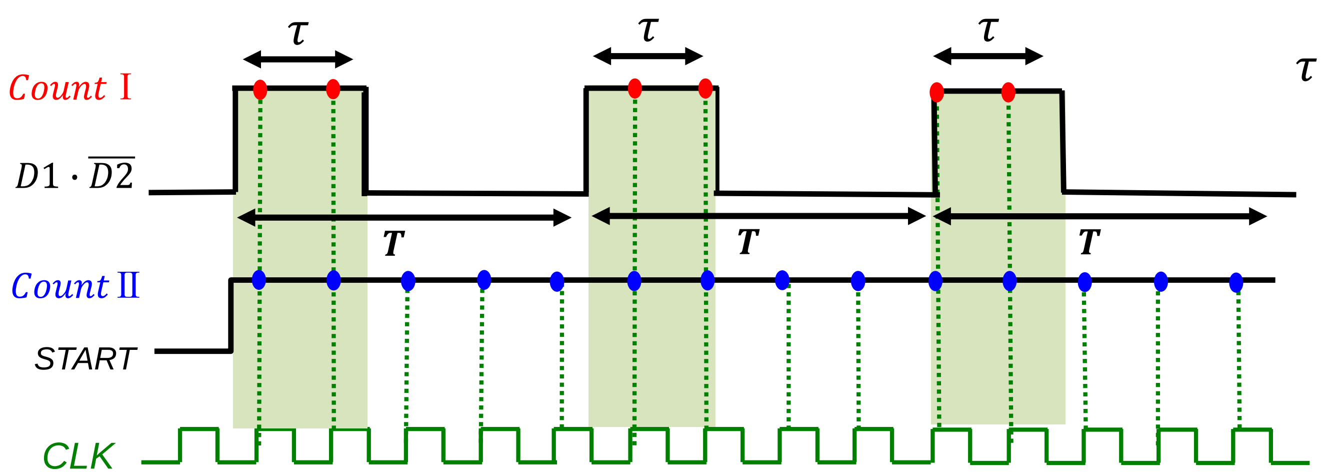
STEP2: Making the square wave with $\boldsymbol{\tau}$ / T duty cycle



Proposed TDC Operation (3/3)



STEP3: Counting the ratio of the sampling points



$$\tau = \frac{Count\ \mathrm{I}}{Count\ \mathrm{II}} T$$

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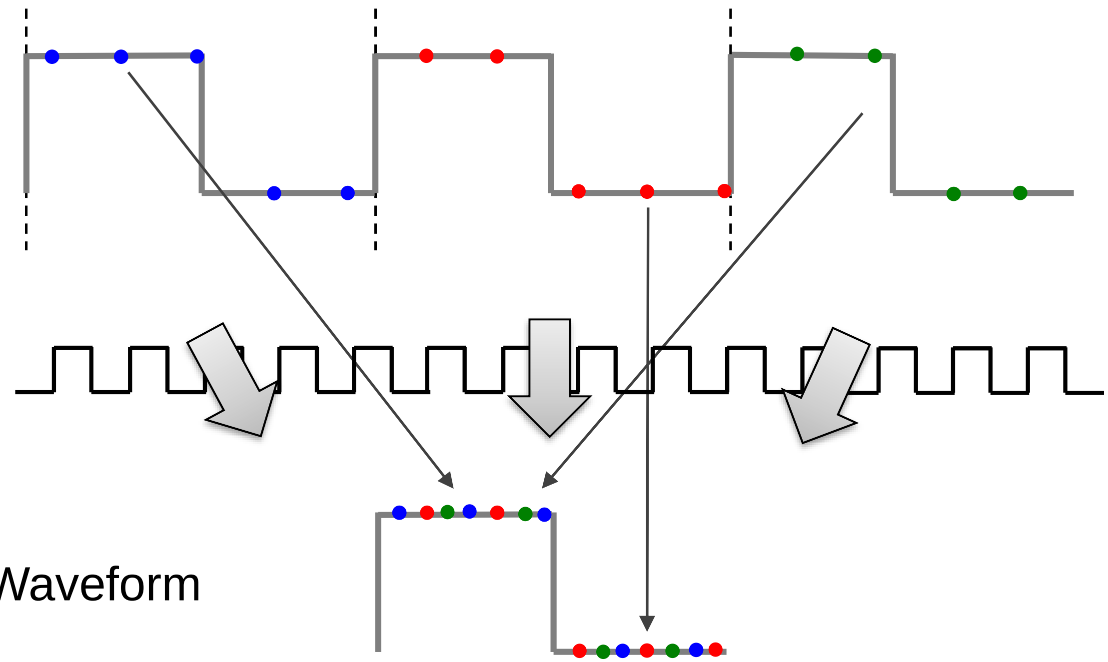
Equivalent-Time Sampling

Measured Wave

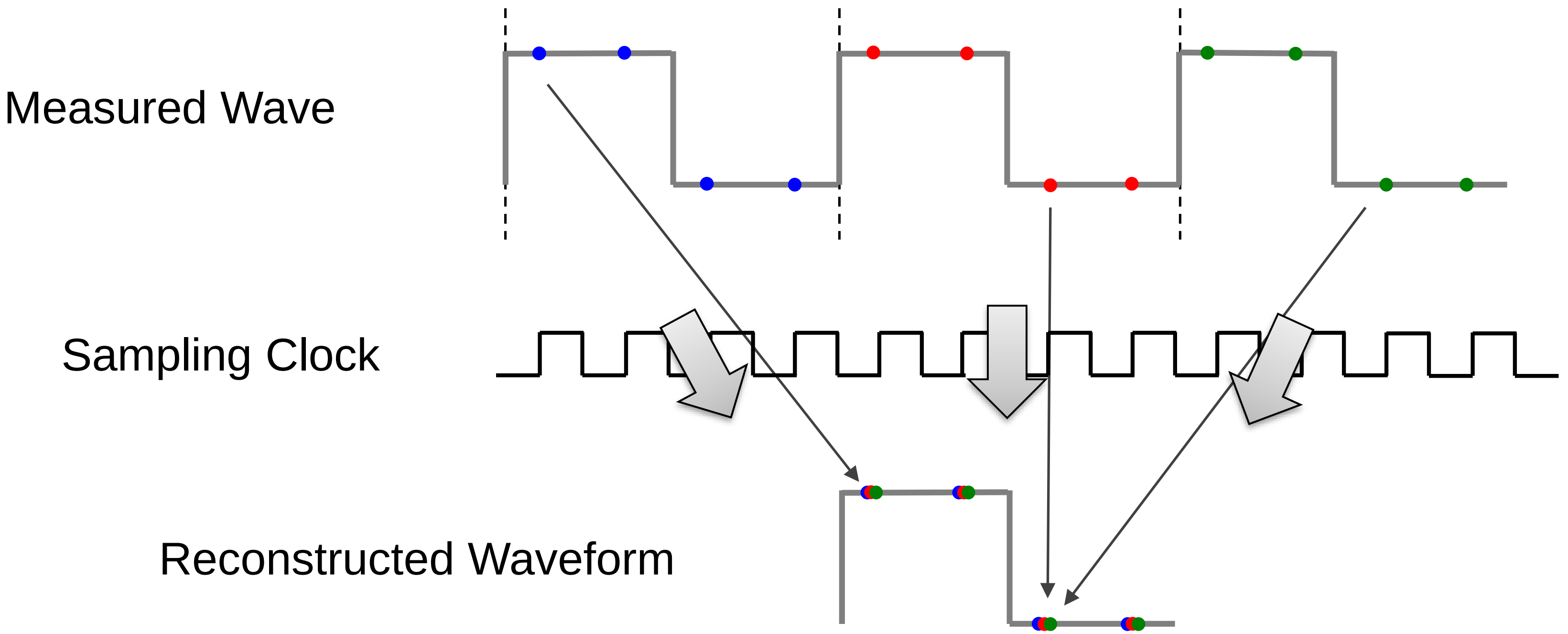
Sampling Clock

Reconstructed Waveform



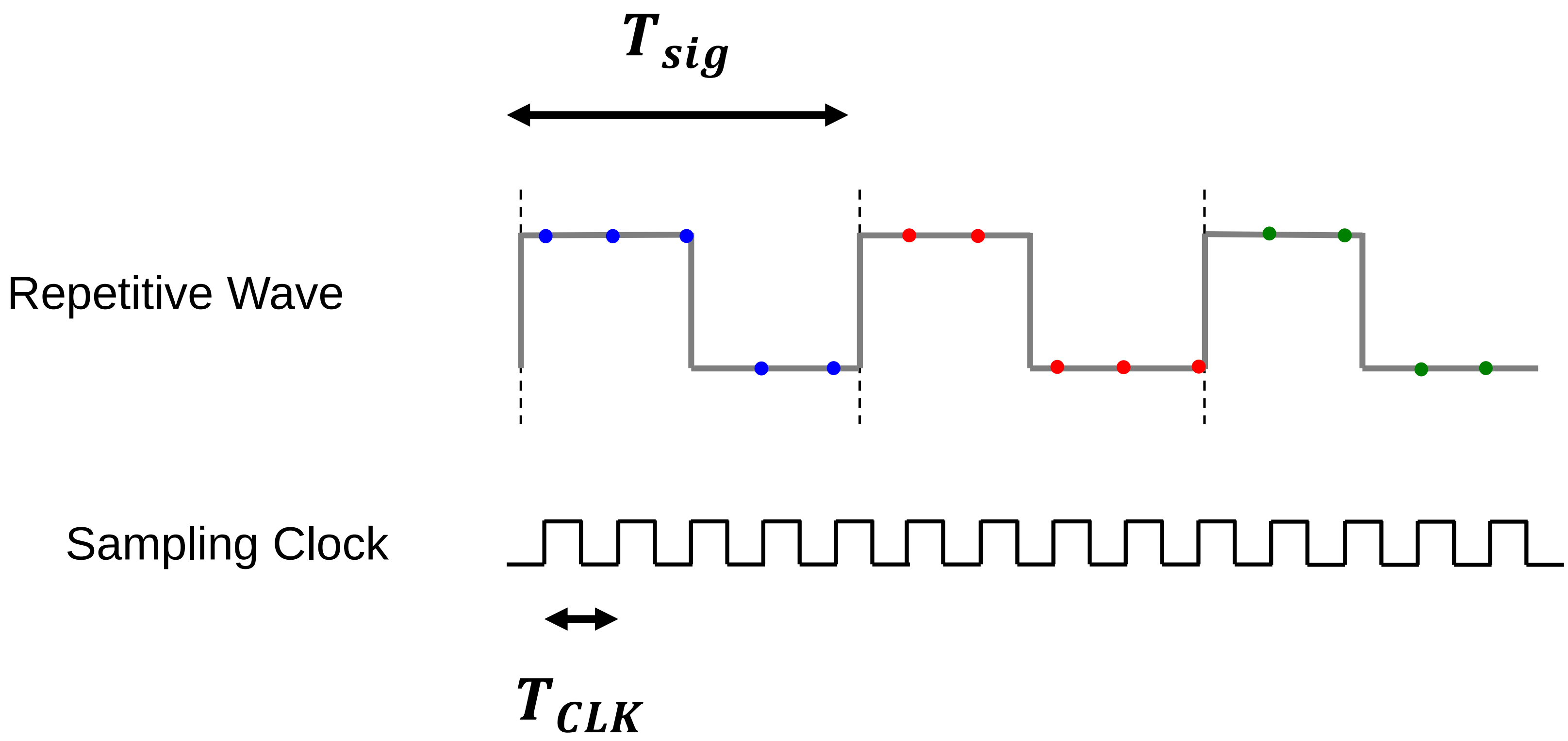
Higher time resolution than sampling clock period

Waveform Missing



Sampling points must be dispersed uniformly

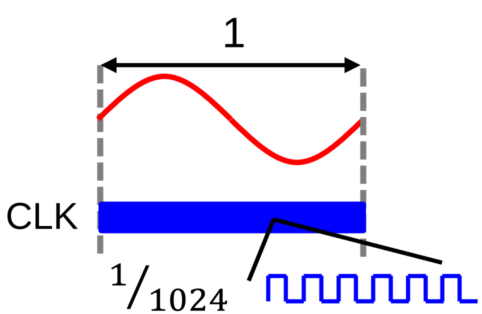
Data Acquisition Condition

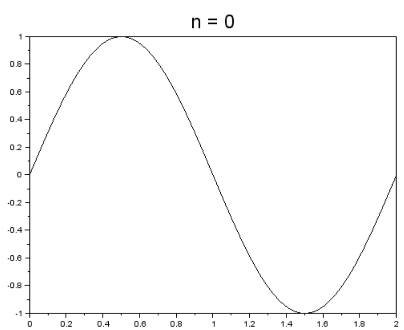


$$T_{CLK} = \boxed{?} \times T_{sig}$$

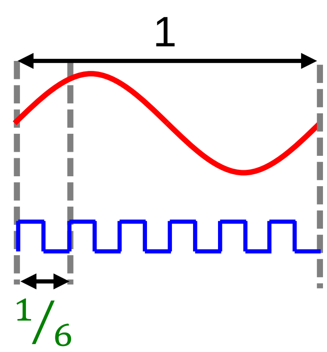
Waveform Missing Condition

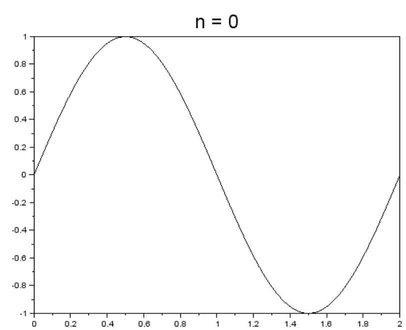
$f_{CLK} \gg f_{sin}$



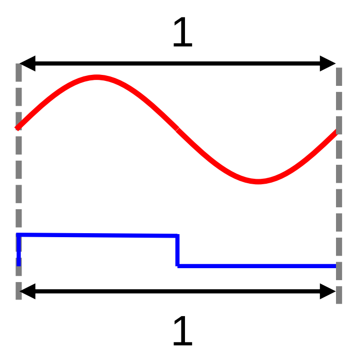


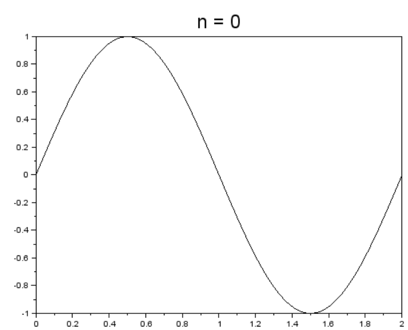
$f_{CLK} \approx \frac{1}{\alpha} f_{sin} \quad \left(\alpha = 1, \frac{1}{2}, \frac{1}{3}, \frac{2}{3}, \cdots, \frac{1}{6}, \cdots\right)$





$f_{CLK} \approx f_{sin}$



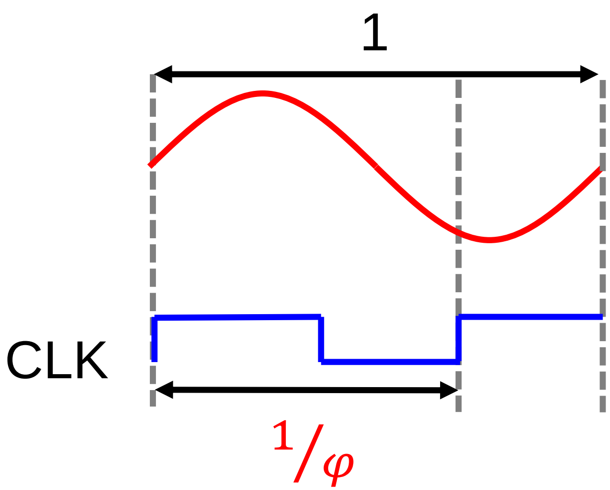


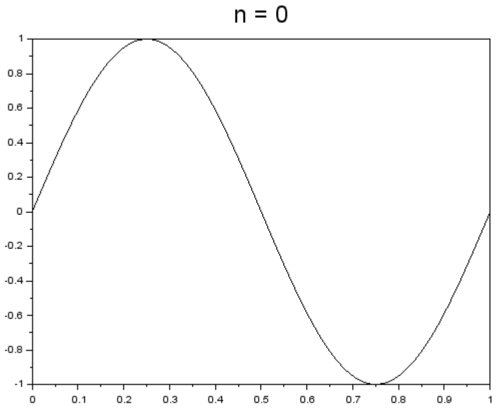
Sampling points move little → Requires long time

Highly Efficient Condition

$$f_{CLK} = \varphi \times f_{sig}$$

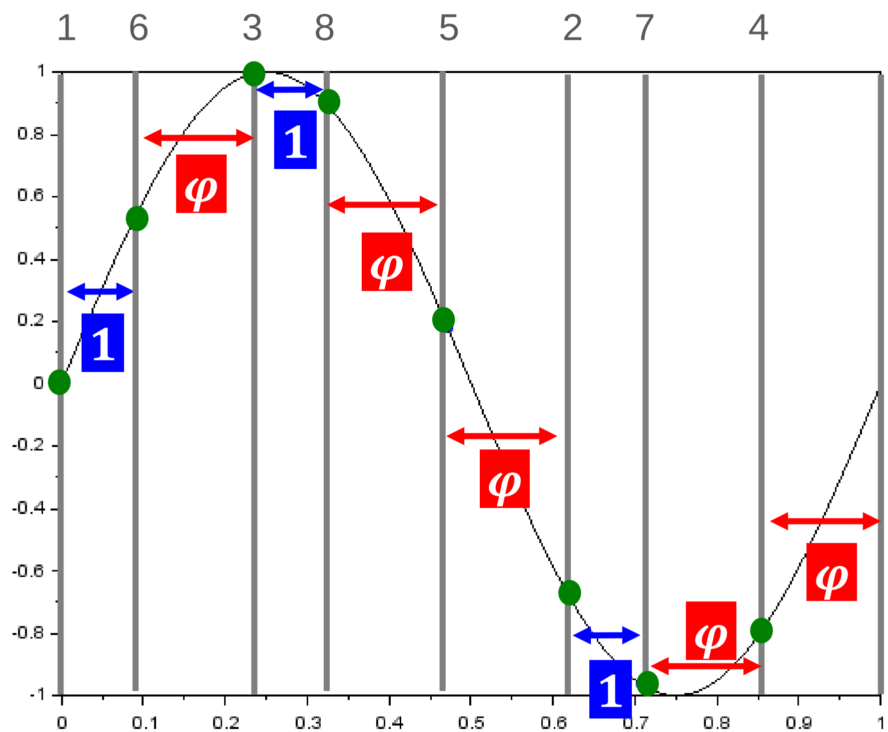
φ : Golden ratio (= 1.6180339887…)





Sampling points are dispersed uniformly through measurement

Golden Ratio Sampling

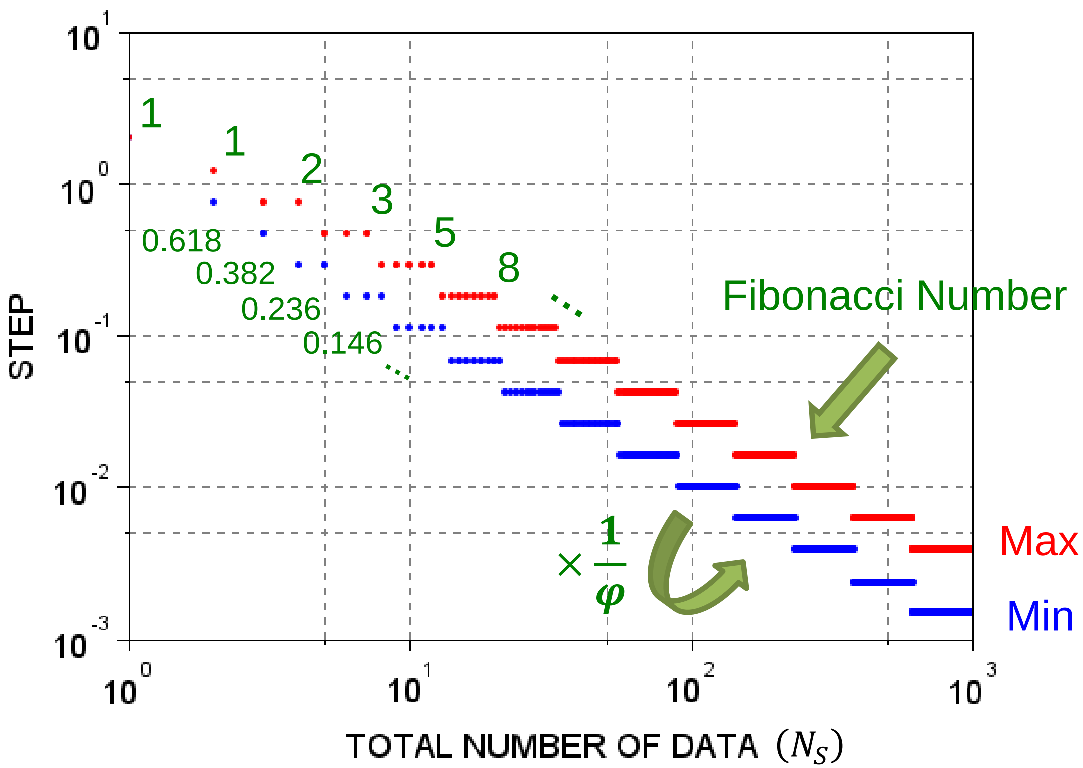


All sections are divided by golden ratio

➡ **Max / Min distances = φ or φ^2 const.**

Time Resolution

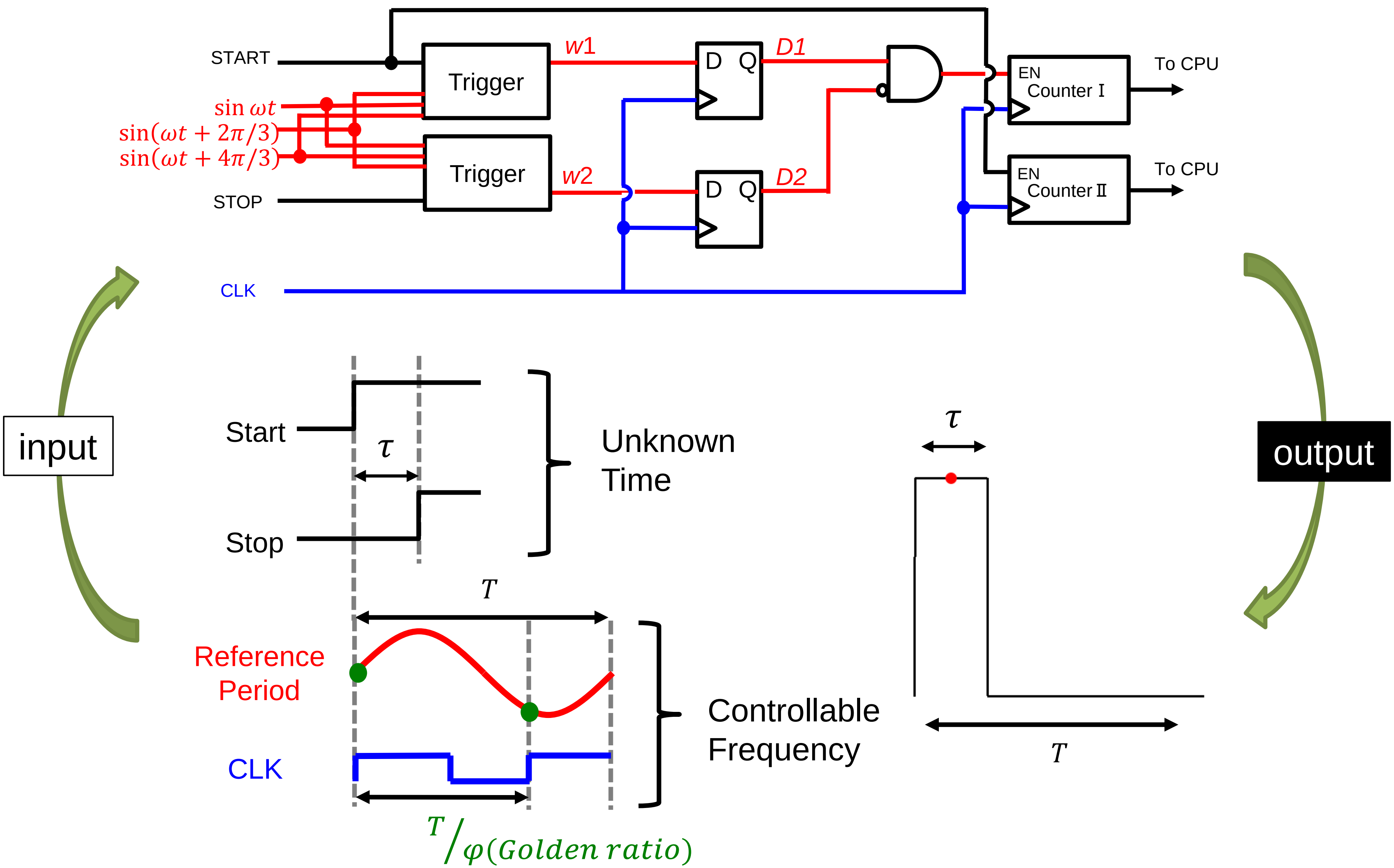
Max & Min distances between neighbor points vs. Total Number of Data



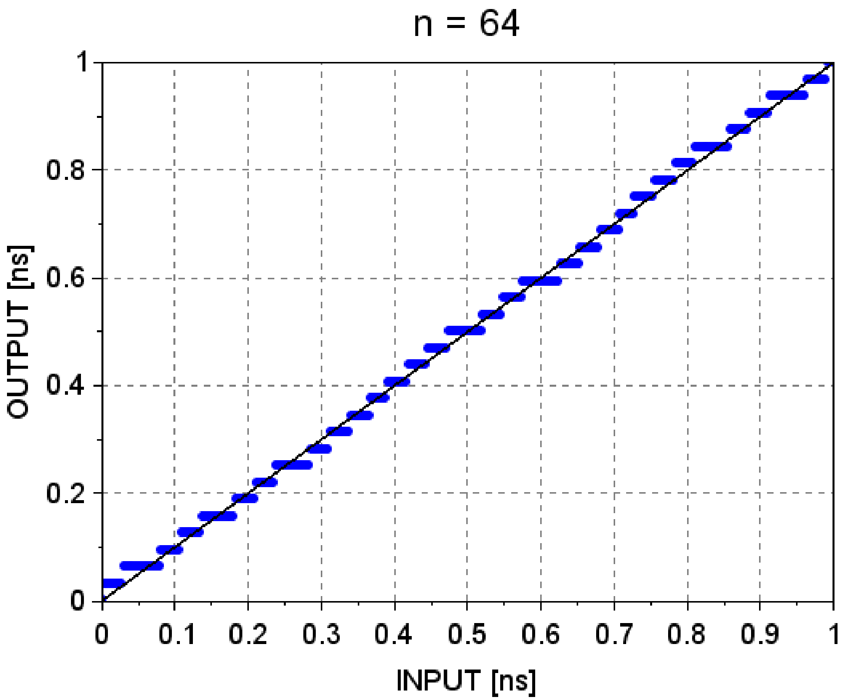
Max & Min distances decreases x 1/Φ every Fibonacci numbers

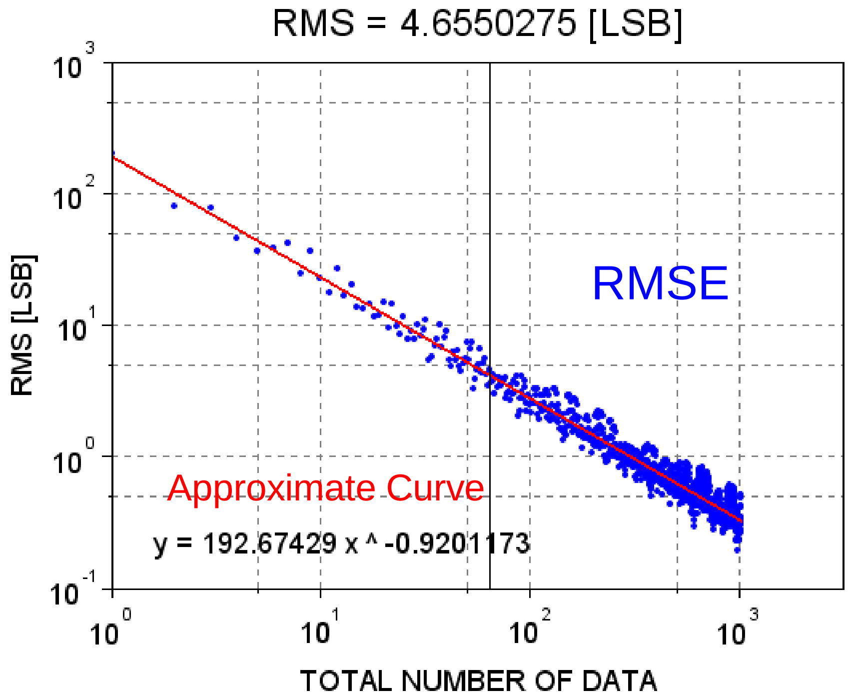
➡ **Time resolution improves about 1 / Total Number of data**

Proposed TDC Data Acquisition



Simulation Result





Acquiring more data improves time resolution

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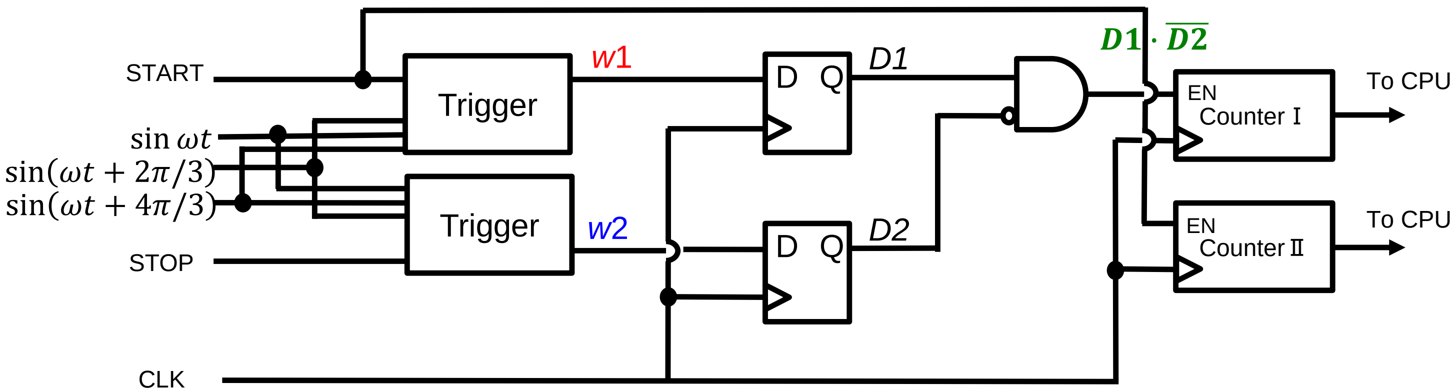
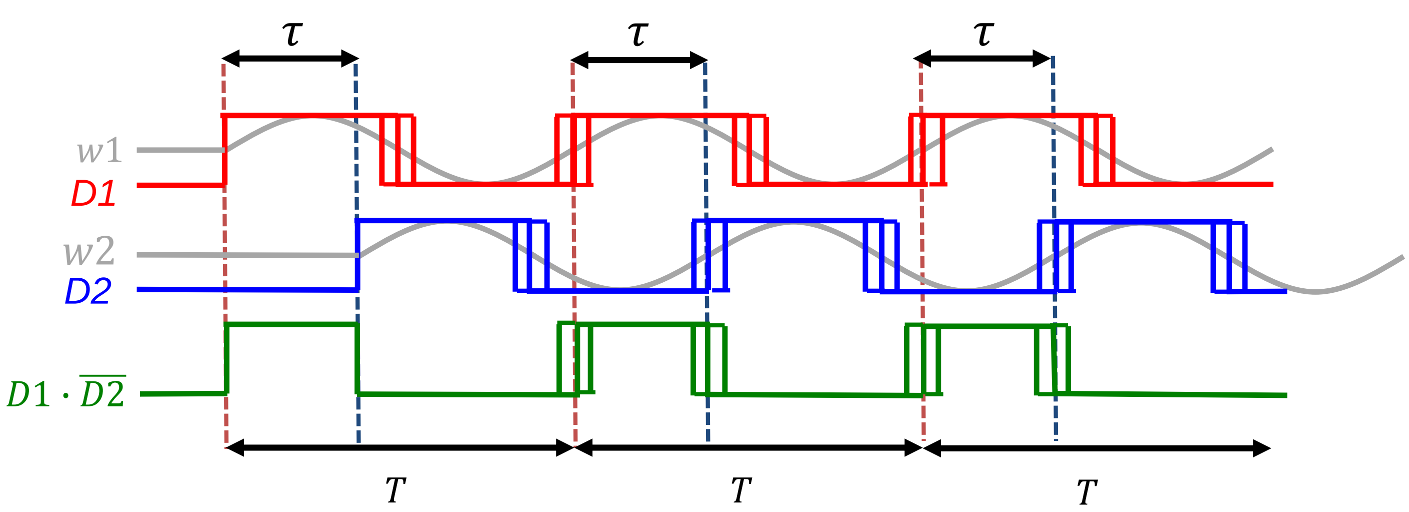
Jitter Effects

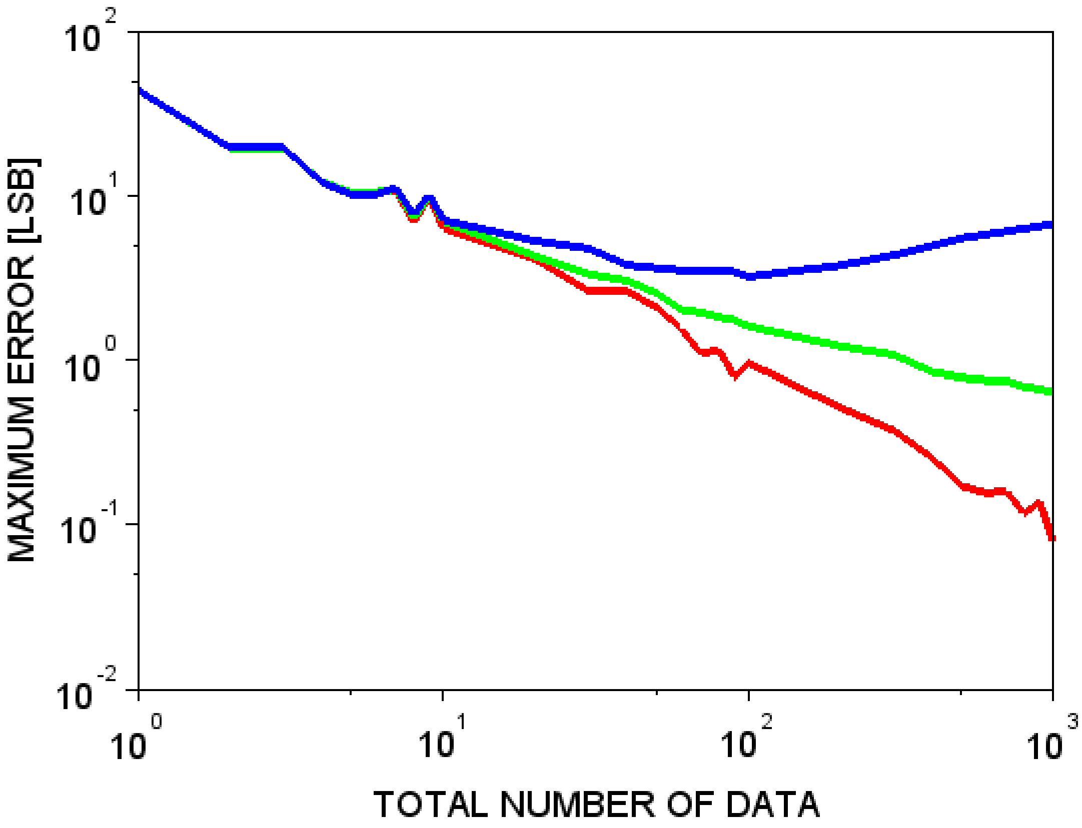


Jitter of w1 & w2 affects period & duty of $D1 \cdot \overline{D2}$



Simulation Result (1/2)

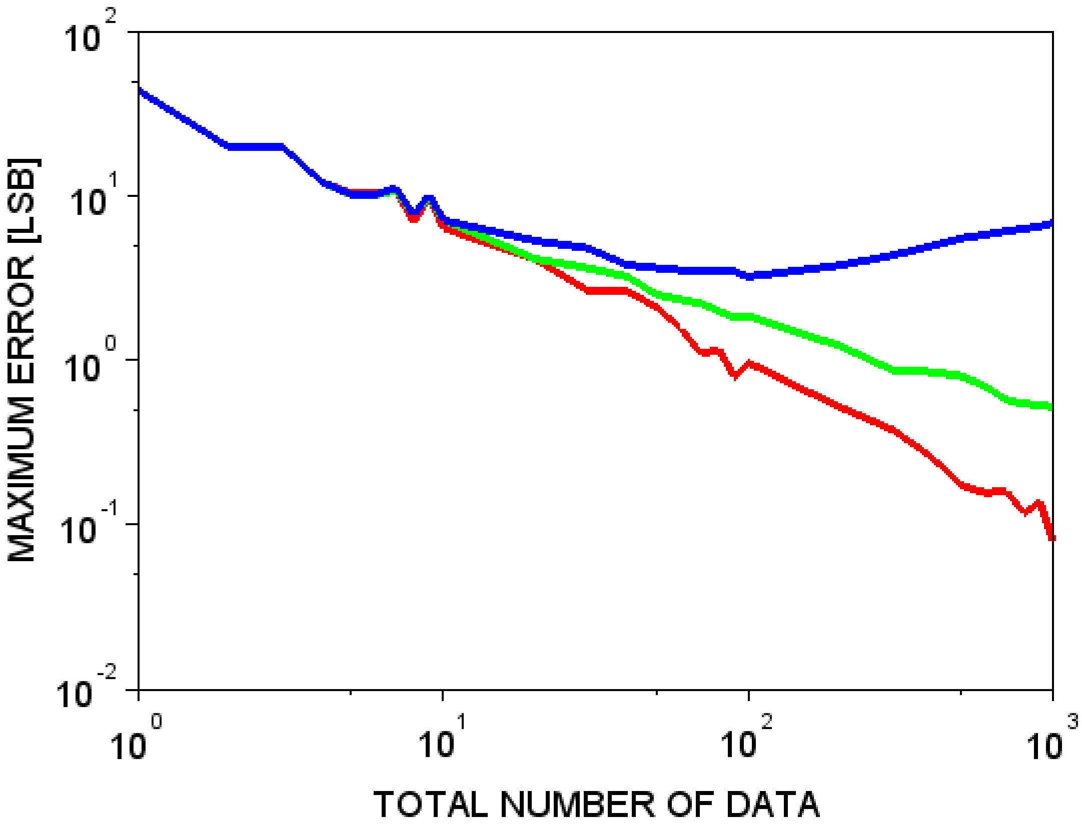
Maximum Error vs. Total Number of Data



No Jitter Random Jitter Accumulated Jitter

Simulation Result (2/2)

Maximum Error vs. Total Number of Data



No Jitter

Common Accumulated Jitter

Differential Accumulated Jitter

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Summary

- Proposed integral-type TDC:
  - fine time resolution
  - no need for calibration
- Highly Efficient Data Acquisition Condition:
  - Sampling clock frequency / measured signal frequency

    = Golden ratio
- Robust for jitter

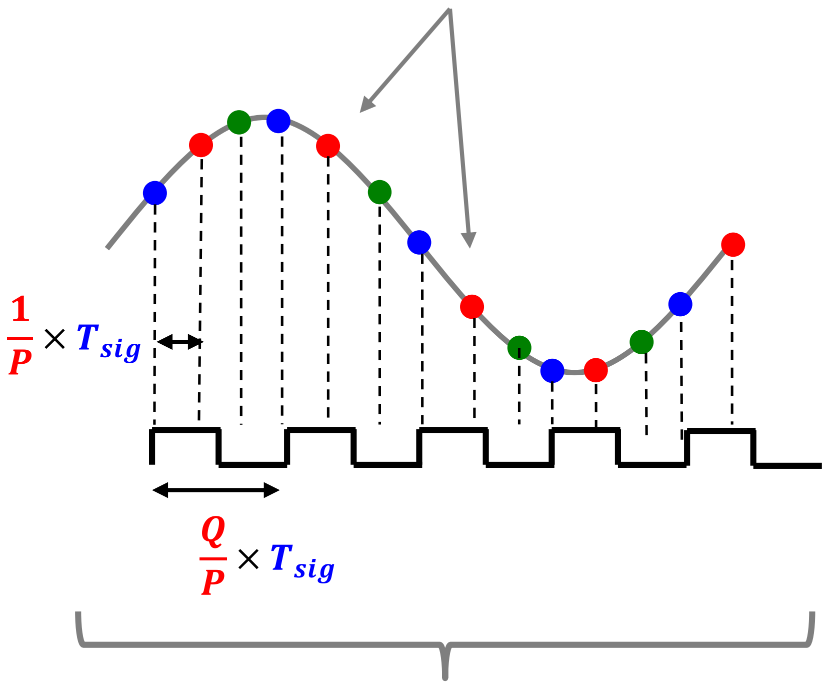
Appendix

Deterministic Measurement

$$T_{CLK} = \frac{Q}{P} \times T_{sig}$$

(P, Q: integers and relatively prime)

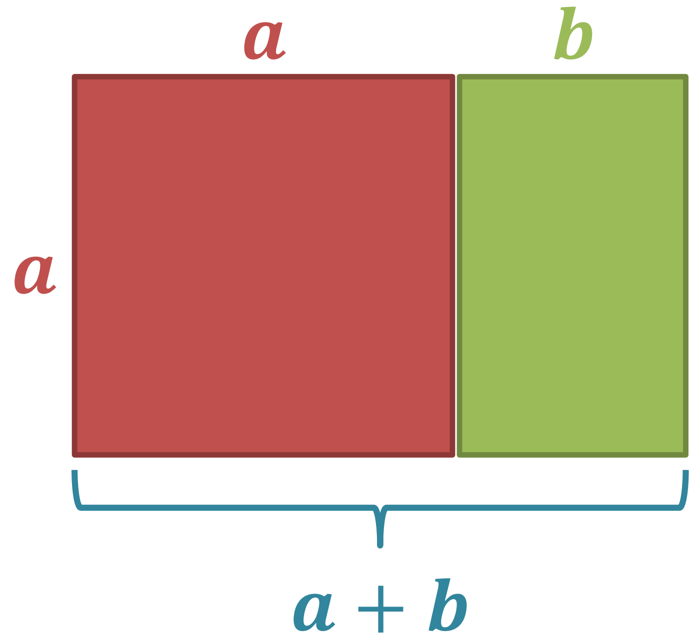
Q: Phase distance for each sampling



P: Maximum number of total measurable sampling points

Golden Ratio

$$\varphi \equiv \frac{a+b}{a} = \frac{a}{b}$$



$$\varphi = \frac{1+\sqrt{5}}{2} = 1.6180339887\cdots$$

Fibonacci Number

$$F_0 = 0$$

$$F_1 = 1$$

$$F_{n+2} = F_n + F_{n+1}$$

$$0, 1, 1, 2, 3, 5, 8, 13, 21, 34, 55, 89, 144, \cdots$$

$$\lim_{n\to\infty} \frac{F_n}{F_{n-1}} = 1.6180339887\cdots = \varphi$$