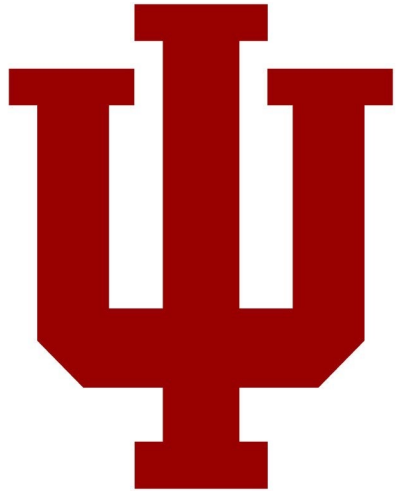
PA: due sooner next year

06 Physically Unclonable Functions (PUFs)

Engr 399/599: Hardware Security

Andrew Lukefahr
Indiana University



Adapted from: Mark Tehranipoor of University of Florida

Course Website

engr599.github.io

Passcode:

Room

2-3-5

Write that down!

Project 1: Hardware Trojan

- Goal: “Corrupt” a working DES implementation
- We give you DES in HW
- You need to:
  - Deploy DES
  - Corrupt DES

Group Assignments

- Chris Sozio
- Will Fleming
- Clare Barnes

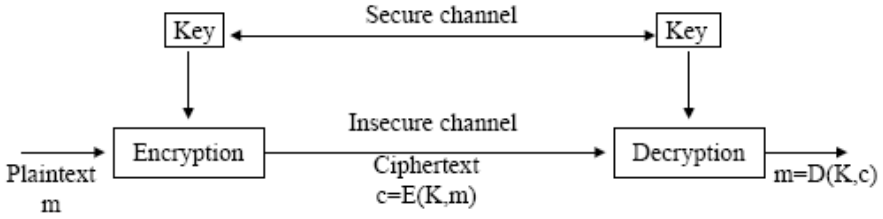
- Austin Parkes
- Max Harms
- Michael Foster

- Trey Peterson
- Yifan Zhang
- Jack Ruocco

Due next Wednesday (?)

Symmetric and Asymmetric Cryptosystems (1)

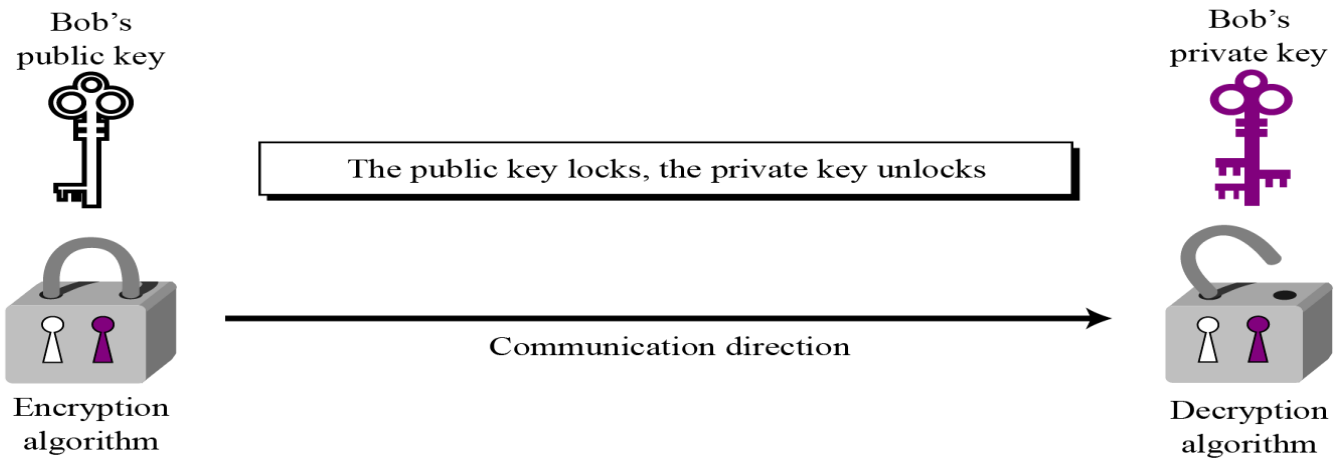
- Symmetric encryption = secret key encryption
  - $K_E = K_D$ — called a secret key or a private key
  - Only sender S and receiver R know the key

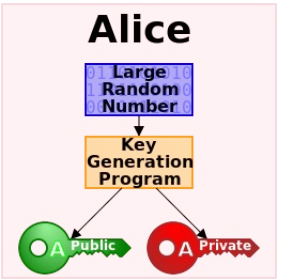


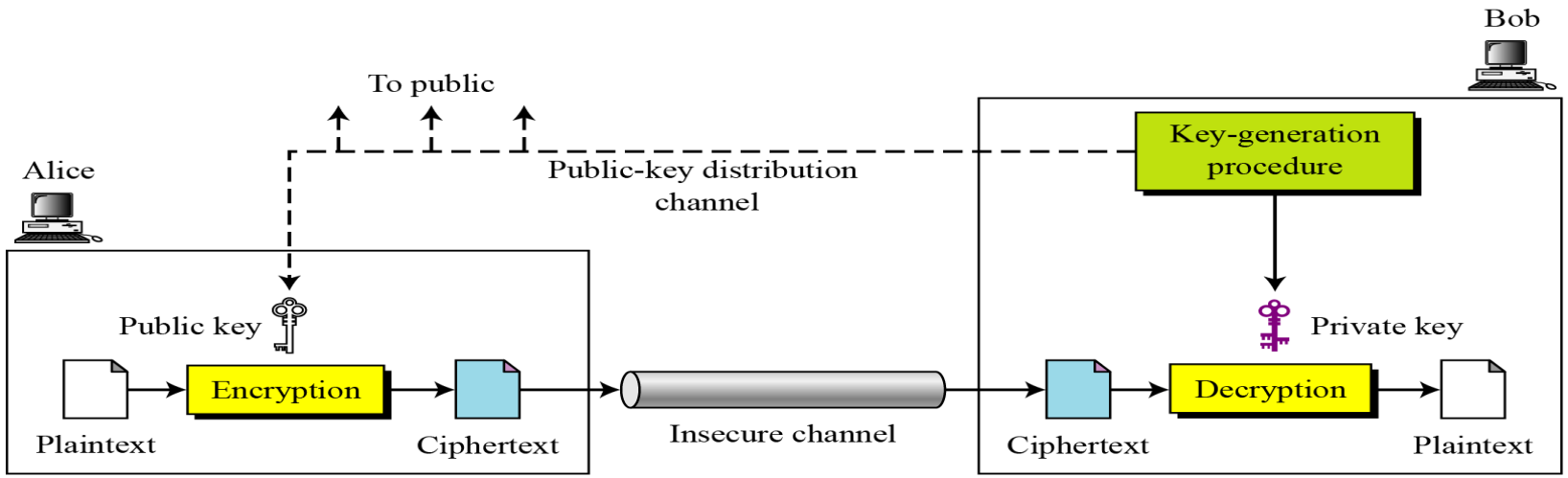
[cf. J. Leiwo]

  - As long as the key remains secret, it also provides authentication (= proof of sender's identity)

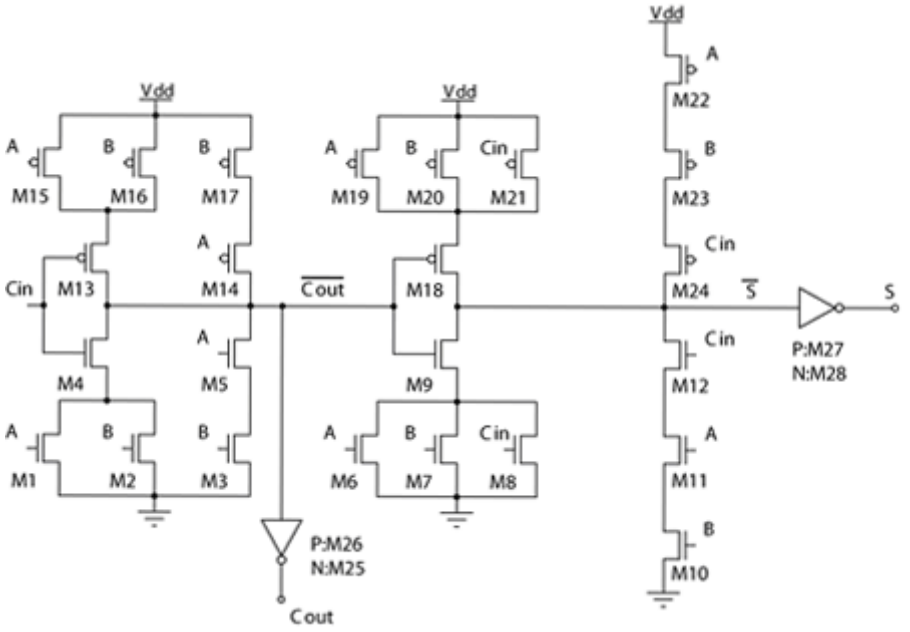
Asymmetric Security

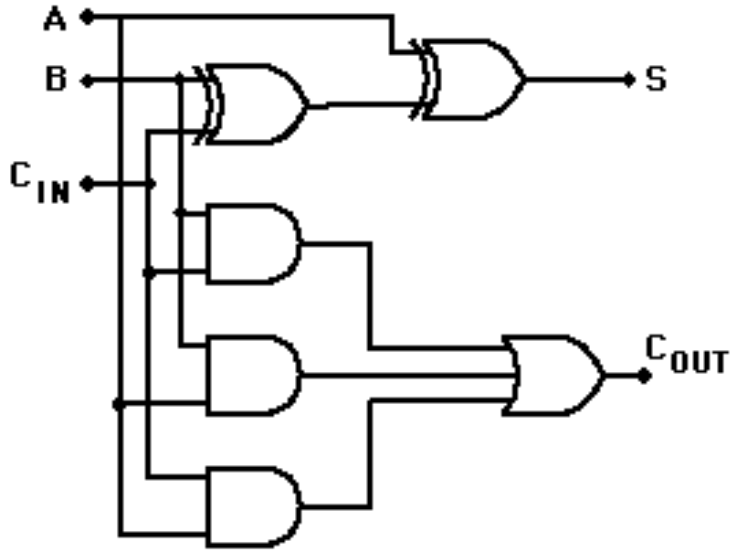


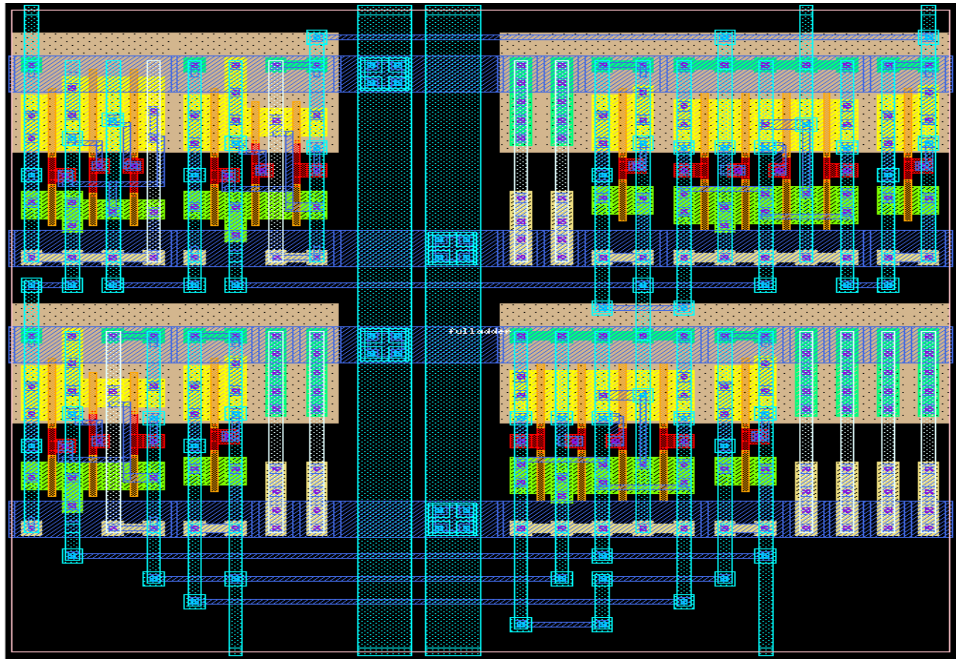


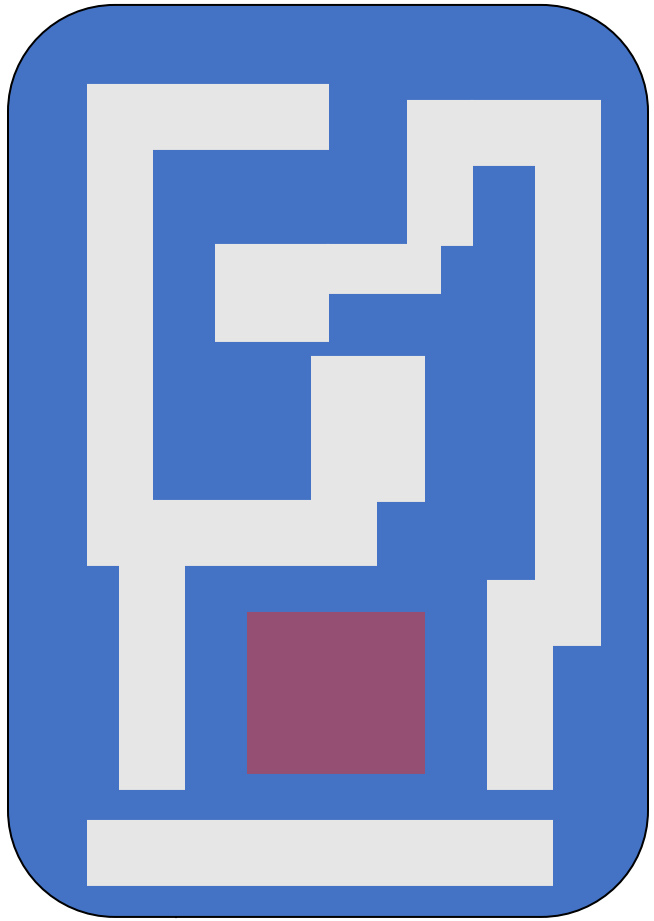


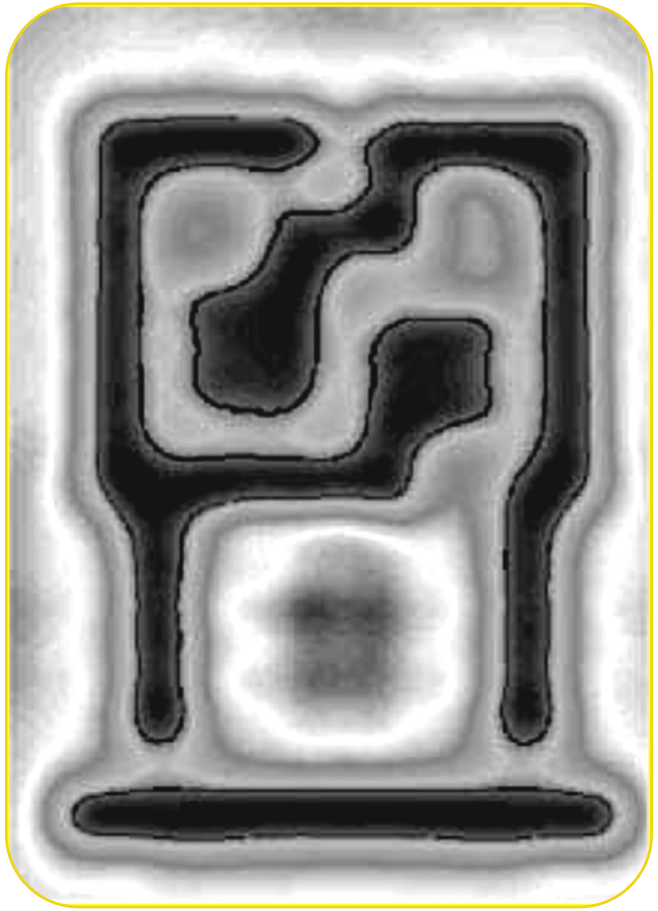
```
module fulladder (a,b,cin,sum,cout);
    input a,b,cin;
    output sum,cout;

    reg sum,cout;
    always @*
    begin
      sum <= a ^ b ^ cin;
      cout <= (a & b) | (a & cin) | (b & cin);
    end
endmodule
```

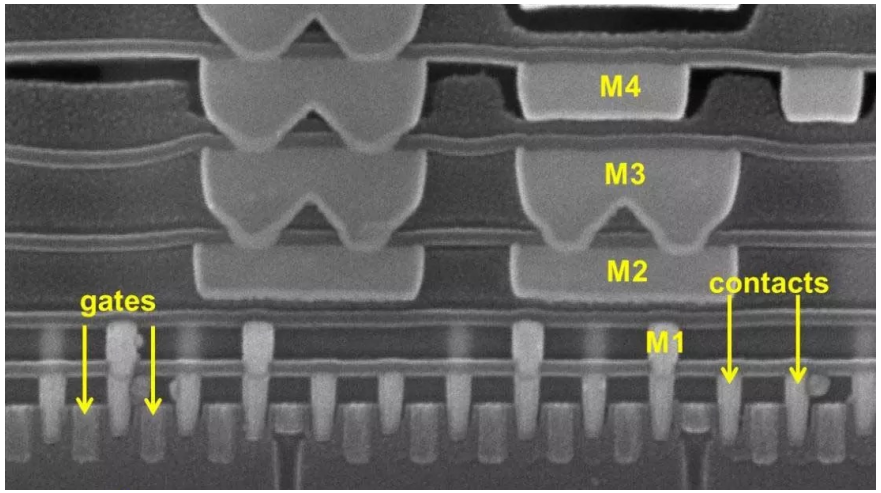










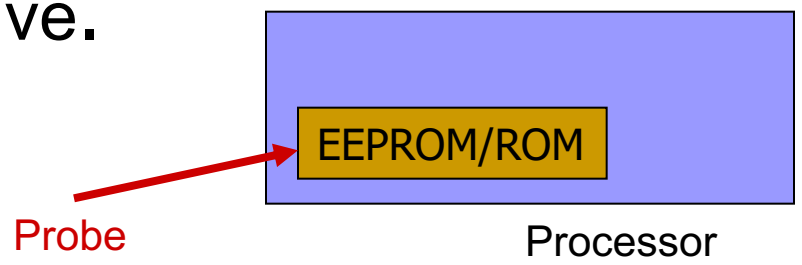

M4
M3
M2
M1
gates
contacts

Security

- Asymmetry b/w the information (secret)
- **One-way functions**
  - Easy to evaluate in one direction but hard to reverse in the other
  - E.g., multiplying large prime number as opposed to factoring them
- **One-way hash functions**
  - Maps a variable length input to a fixed length output
  - **Avalanche property**: changing one bit in the input alters nearly half of the output bits
  - Pre-image resistant, collision resistant
  - Usage: digital signature, secured password storage, file identification, and message authentication code

Problem

Storing digital information in a device in a way that is resistant to physical attacks is difficult and expensive.



- Adversaries can physically extract secret keys from EEPROM while processor is off
- Trusted party must embed and test secret keys in a secure location
- EEPROM adds additional complexity to manufacturing

IBM 4758

Problem:

Storing digital information in a device in a way that is resistant to physical attack is difficult and expensive.

IBM 4758

Tamper-proof package containing a secure processor which has a secret key and memory

- Tens of sensors, resistance, temperature, voltage, etc.

- Continually battery-powered

~ $3000 for a 99 MHz processor and 128MB of memory

Challenges of algorithmic (mathematical) one-way functions

- **Technological**
  - Massive number of parallel devices broke DES
  - Reverse-engineering of secure processors
- **Fundamental**
  - There is no proof that attacks do not exist
  - E.g., quantum computers could factor two large prime numbers in polynomial time
- **Practical**
  - Embedded systems applications

Solution -- POWF

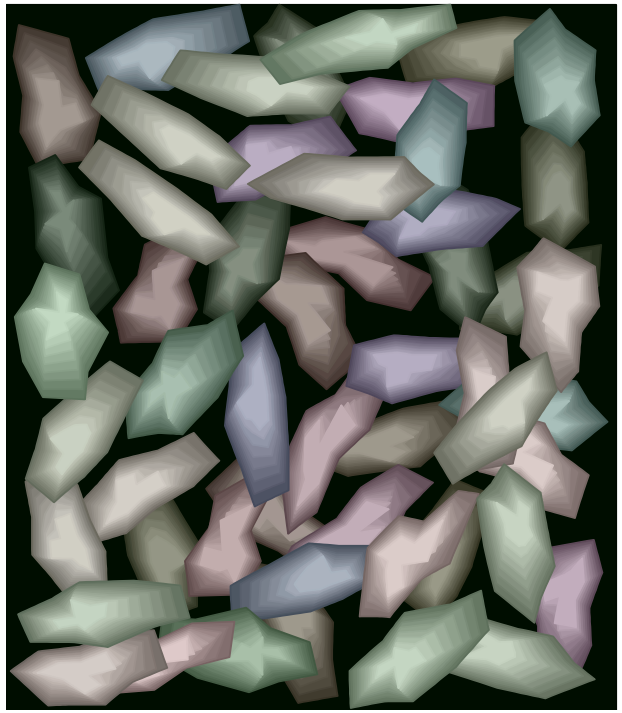
- Use the chaotic physical structures that are hard to model instead of mathematical one-way functions!
- Physical One Way Functions (POWF)
  - Inexpensive to fabricate
  - Prohibitively difficult to duplicate
  - No compact mathematical representation
  - Intrinsically tamper-resistant

Feature: Process Variation

- Do we expect process variation (length, widths, oxide thickness) in circuit and system?
  - Impact circuit performance
  - Functional failure
  - Major obstacle to the continued scaling of integrated-circuit technology in the sub-45 nm regime
- Process variations can be turned into a feature rather than a problem?
  - Each IC has unique properties

Solution

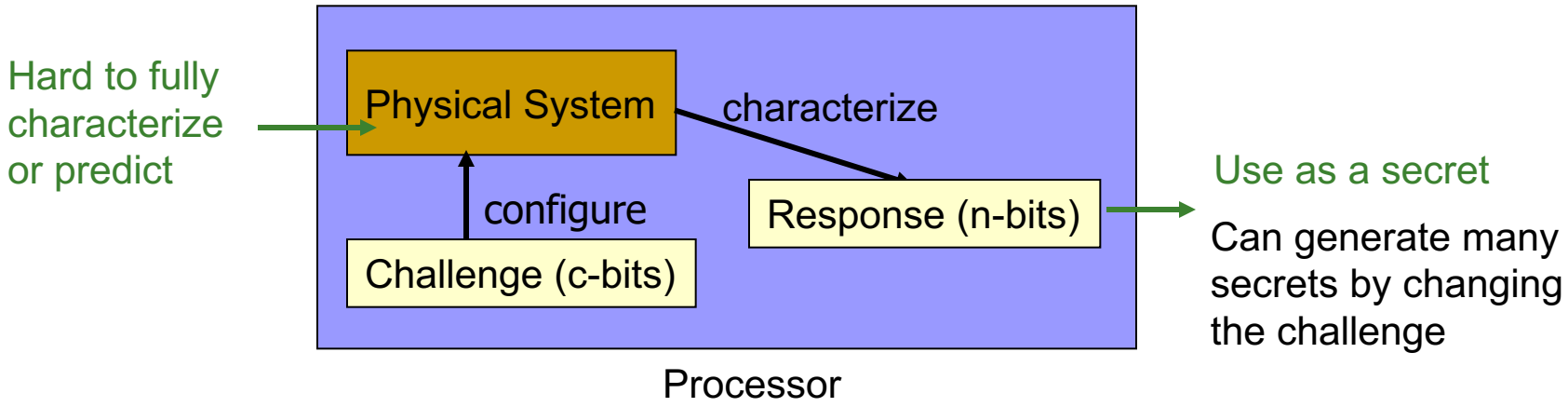
Extract key information from a complex physical system.



Devadas, et. al, DAC02

Physical Unclonable/Random Functions (PUFs)

- Generate keys from a complex physical system



- Security Advantage
  - Keys are generated on demand → No non-volatile secrets
  - No need to program the secret
  - Can generate multiple master keys
- What can be hard to predict, but easy to measure?

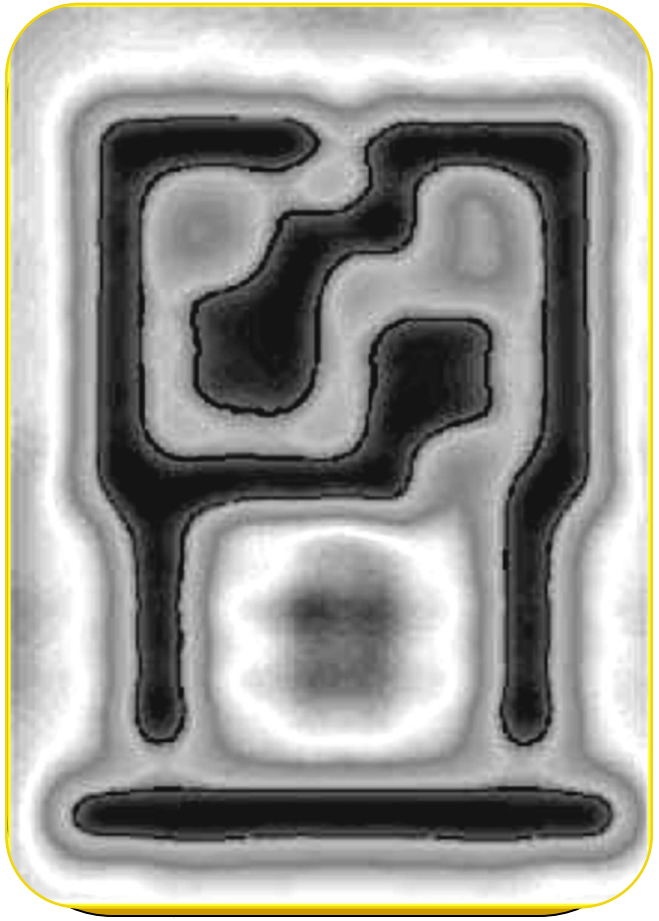
Definition

A Physical Random Function or Physical Unclonable Function (PUF) is a function that is:

- Based on a physical system
- Easy to evaluate (using the physical system)
- Its output looks like a random function
- Unpredictable even for an attacker with physical access

WYSINWYG

Sub-Wavelength WYSINWYG



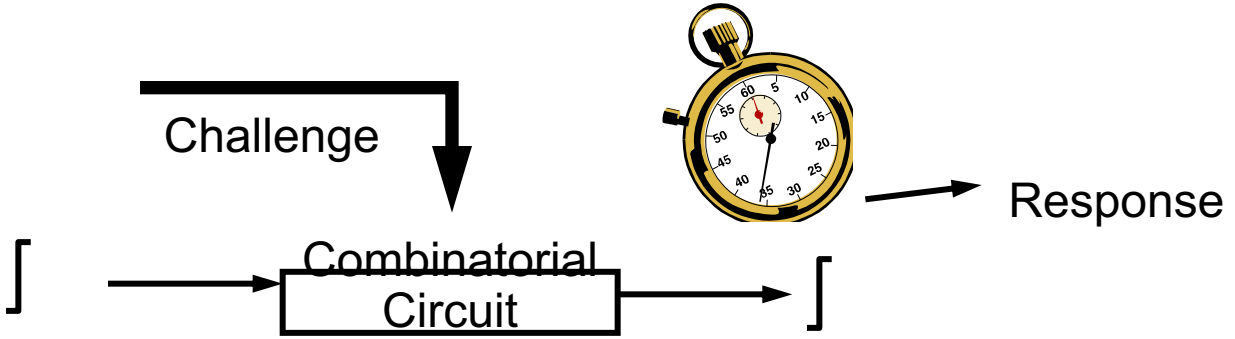
What You See Is Not What You Get

Process variations

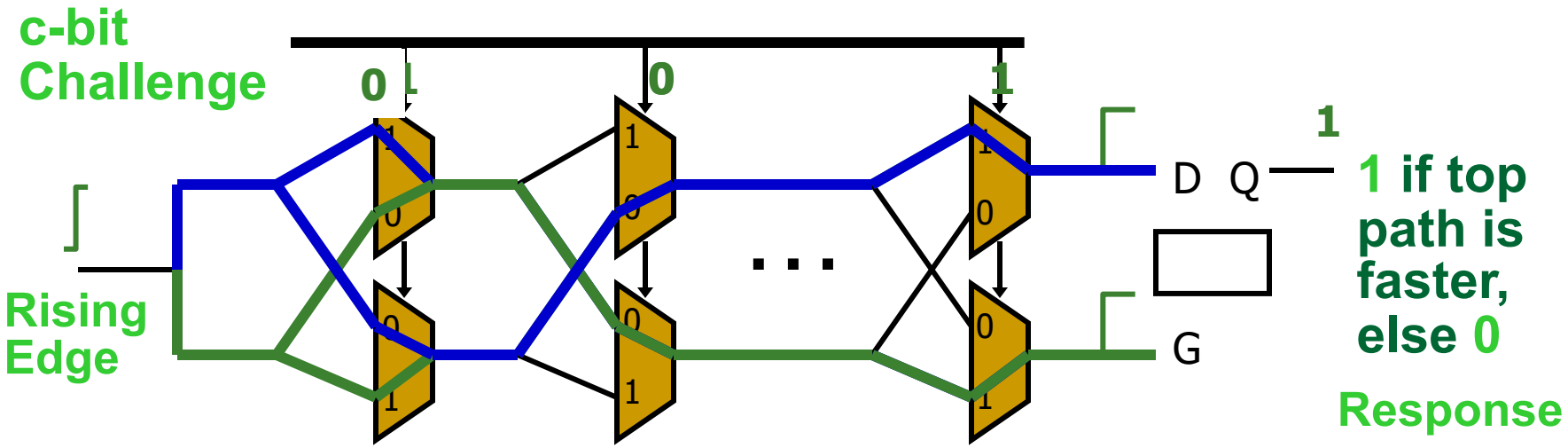
No two transistors have the same parameters

Silicon PUF – Proof of Concept

- Because of process variations, no two Integrated Circuits are identical
- Experiments in which *identical circuits with identical layouts* were placed on different FPGAs show that path delays vary enough across ICs to use them for identification.



A Candidate: Silicon PUF



- Compare two paths with an identical delay in design
  - Random process variation determines which path is faster
  - An arbiter outputs 1-bit digital response
- **Path delays in an IC are statistically distributed due to random manufacturing variations**

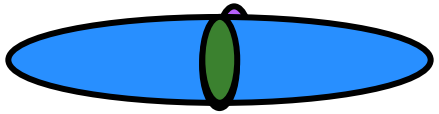
Experiments

- Fabricated candidate PUF on multiple ICs, 0.18um TSMC
- Apply 100 random challenges and observe responses

100 bits of response

Distance between Chip X and Y responses = 24 bits

At 70C measurement noise for chip X = 2



Measurement noise for Chip X = 0.5

Can identify individual ICs

Measurement Attacks and Software Attacks

Can an adversary create a *software clone* of a given PUF chip?

Distance between Chip X and Y responses = 24

At 70C measurement noise for chip X = 2

Measurement noise for Chip X = 0.5

Measurement Attacks and Software Attacks

Can an adversary create a *software clone* of a given PUF chip?

Distance between Chip X and Y responses = 24

At 70C measurement noise for chip X = 2

Measurement noise for Chip X = 0.5

Model-building appears hard even for simple circuits

"Best" model for Chip X has error = 10

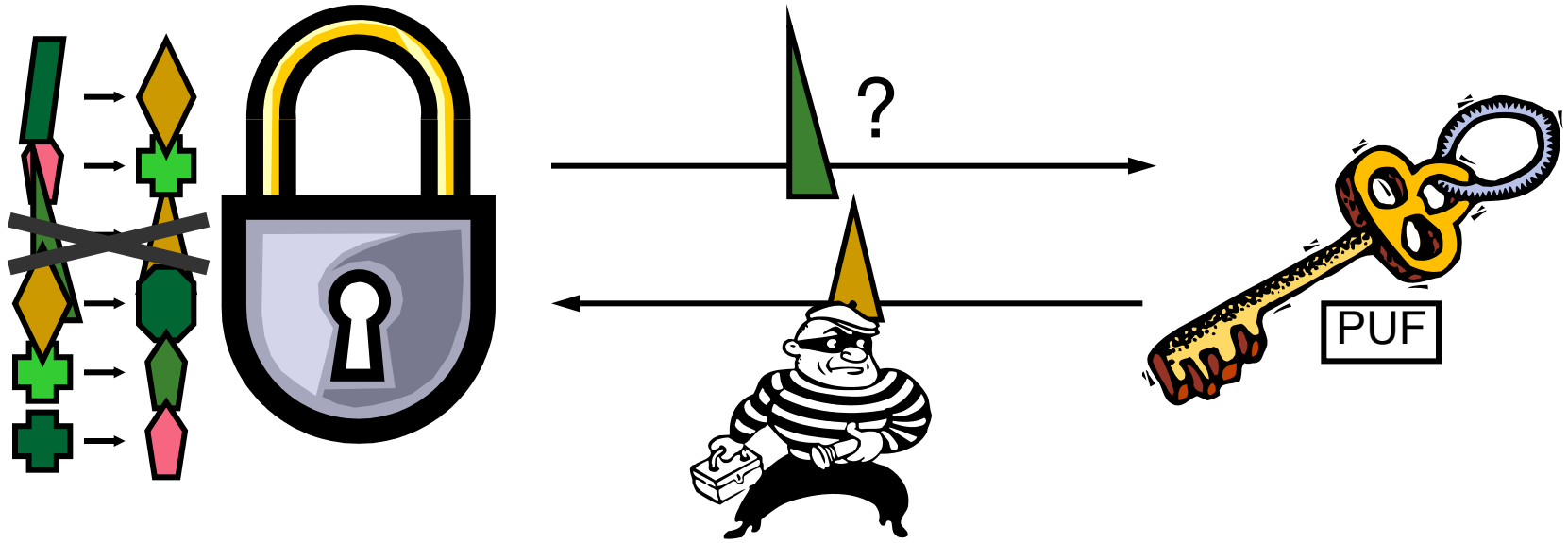
Physical Attacks

- Make PUF delays depend on overlaid metal layers and package
- Invasive attack (e.g., package removal) changes PUF delays and destroys PUF
- Non-invasive attacks are still possible
  - To find wire delays one needs to find precise relative timing of transient signals as opposed to looking for 0's and 1's
  - Wire delay is not a number but a function of challenge bits and adjacent wire voltages and capacitances

Using a PUF as an Unclonable Key

A Silicon PUF can be used as an unclonable key.

- **The lock has a database of challenge-response pairs.**
- **To open the lock, the key has to show that it knows the response to one or more challenges.**



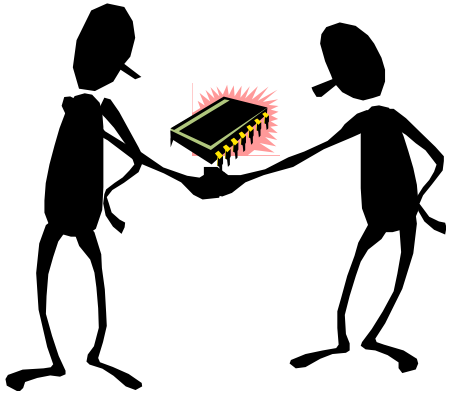
Applications

- **Anonymous Computation**

  Alice wants to run computations on Bob's computer, and wants to make sure that she is getting correct results. A certificate is returned with her results to show that they were correctly executed.

- **Software Licensing**

  Alice wants to sell Bob a program which will only run on Bob's chip (identified by a PUF). The program is copy-protected so it will not run on any other chip.



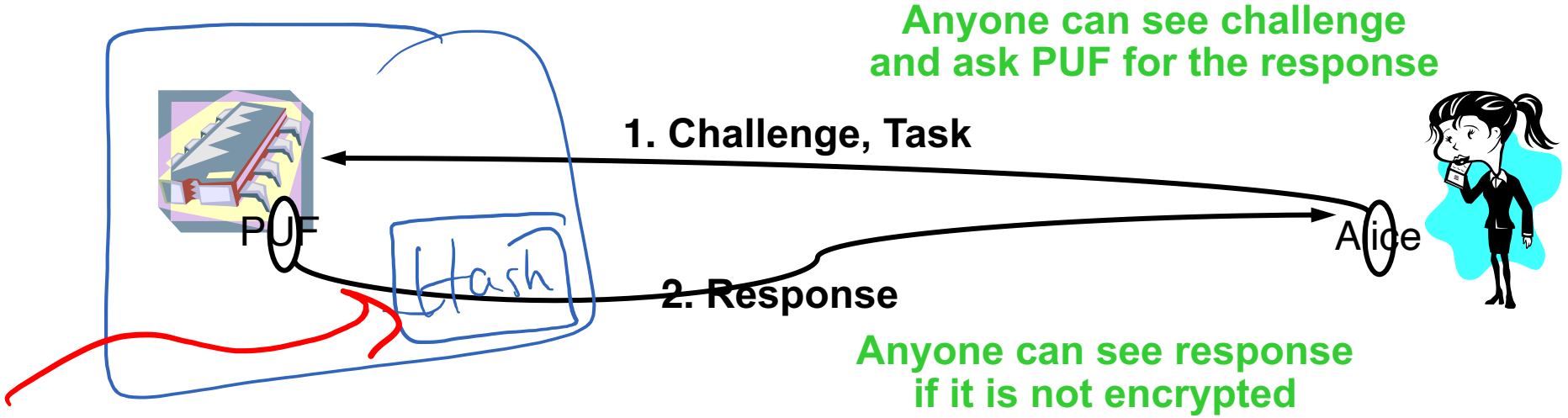
We can enable the above applications by trusting only a single-chip processor that contains a silicon PUF.

Sharing a Secret with a Silicon PUF

Suppose Alice wishes to share a secret with the silicon PUF

She has a challenge response pair that no one else knows, which can authenticate the PUF

She asks the PUF for the response to a challenge

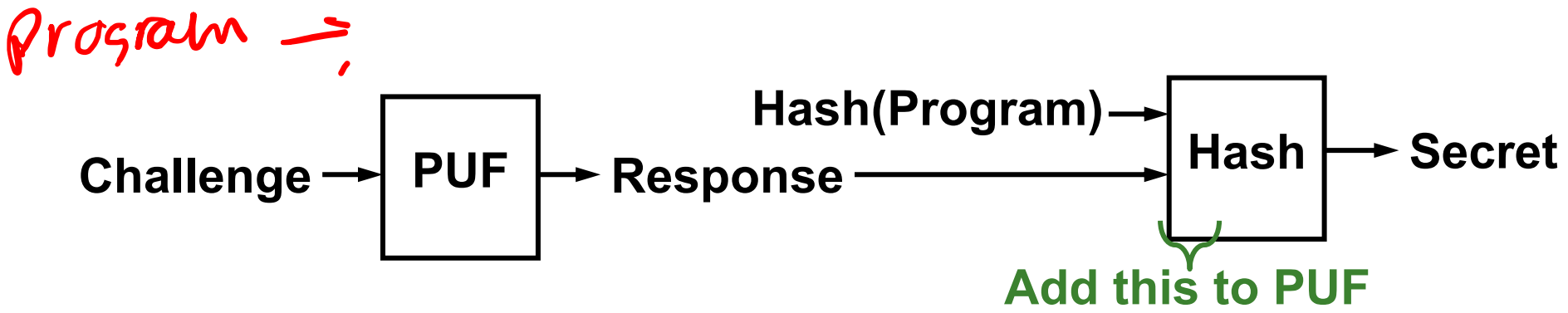


Restricting Access to the PUF

- To prevent the attack, the man in the middle must be prevented from finding out the response.
- Alice's program must be able to establish a shared secret with the PUF, the attacker's program must not be able to get the secret.

⇒ **Combine response with hash of program.**

- **The PUF can only be accessed via the GetSecret function:**



Cryptographic Hash Function

- Crypto hash function $h(x)$ must provide
  - **Compression** — output length is small
  - **Efficiency** — $h(x)$ easy to compute for any x
  - **One-way** — given a value y it is infeasible to find an x such that $h(x) = y$
  - **Weak collision resistance** — given x and $h(x)$, infeasible to find $y \neq x$ such that $h(y) = h(x)$
  - **Strong collision resistance** — infeasible to find any x and y, with $x \neq y$ such that $h(x) = h(y)$

Getting a Challenge-Response Pair

- Now Alice can use a Challenge-Response pair to generate a shared secret with the PUF equipped device.

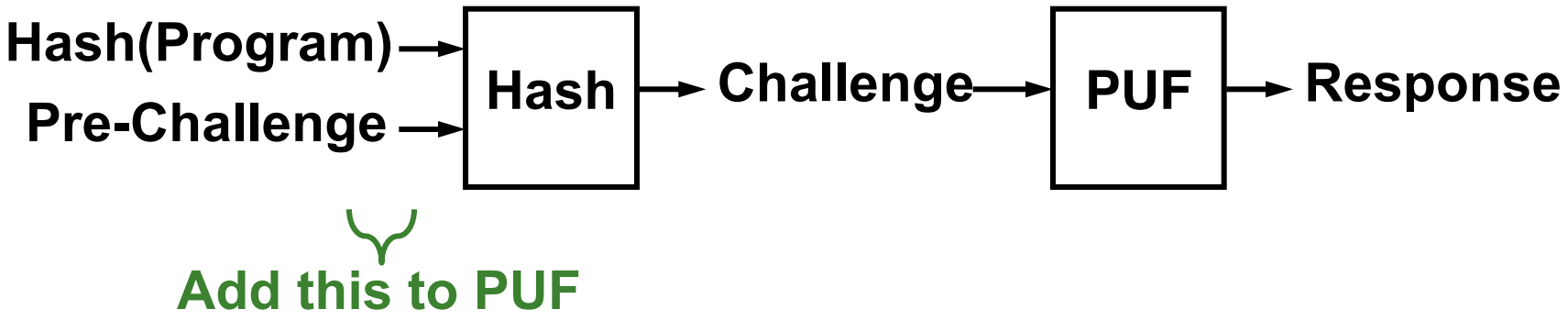
- But Alice can't get a Challenge-Response pair in the first place since the PUF never releases responses directly.

  $\Rightarrow$ **An extra function that can return responses is needed.**

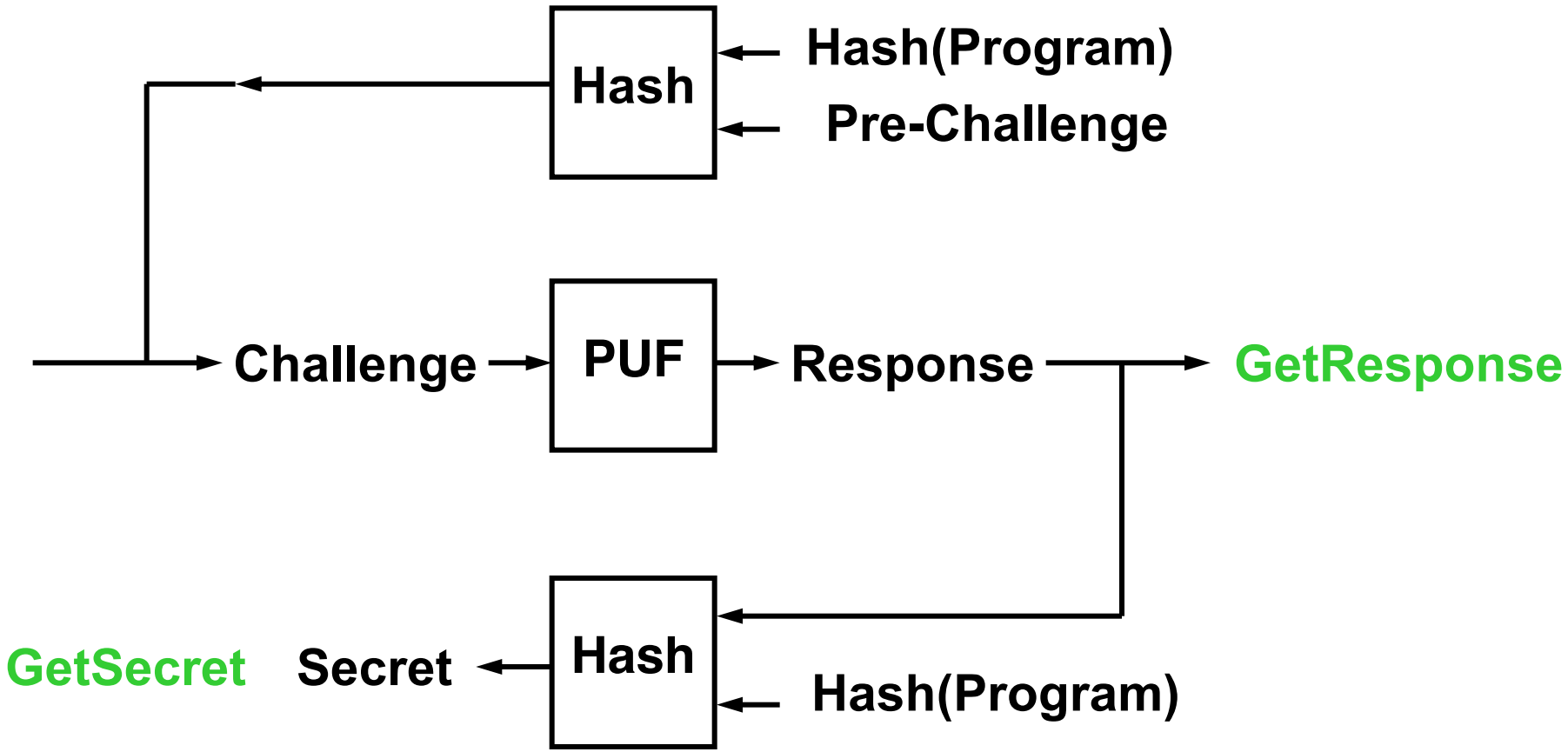
Getting a Challenge-Response Pair – 2

- Let Alice use a Pre-Challenge.
- Use program hash to prevent eavesdroppers from using the pre-challenge.

- The PUF has a GetResponse function



Controlled PUF Implementation



Software Licensing

Program (Ecode, Challenge)

Secret = GetSecret(Challenge)

Code = Decrypt(Ecode, Secret) } **Hash(Program)**

Run Code

Ecode has been encrypted with Secret by Manufacturer

Secret is known to the manufacturer because he knows Response to Challenge and can compute

Secret = Hash(Hash(Program), Response)

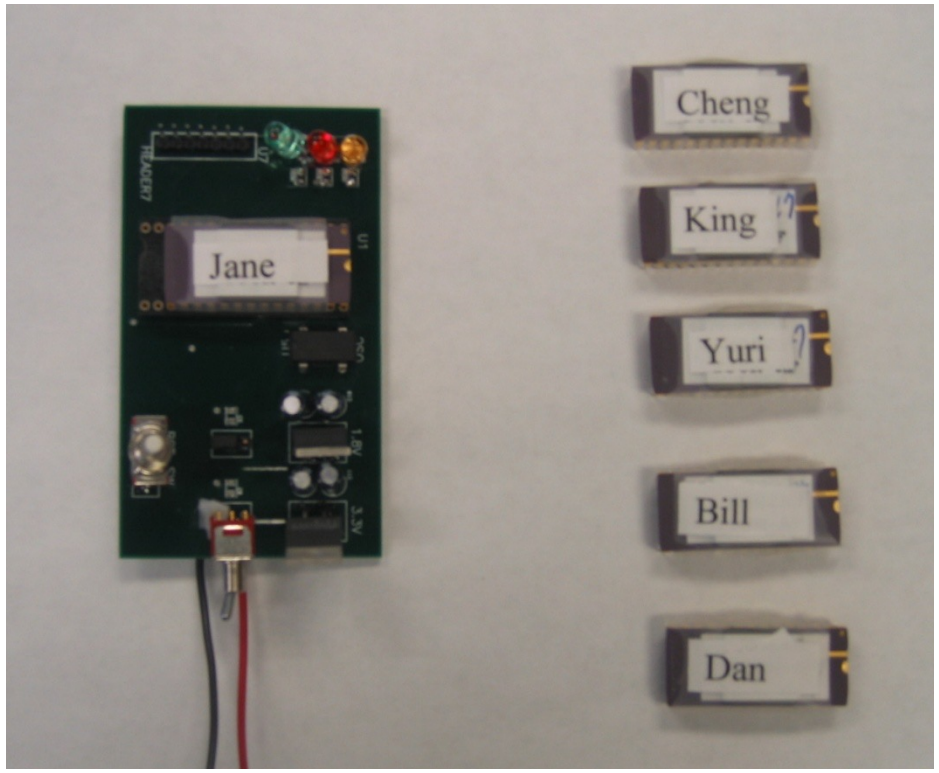
Adversary cannot determine Secret because he does not know Response or Pre-Challenge

If adversary tries a different program, a different secret will be generated because Hash(Program) is different

More on Physically Unclonable Functions (PUFs)

PUF Experiments

- Fabricated 200 “identical” chips with PUFs in TSMC 0.18μ on 5 different wafer runs



Security

– What is the probability that a challenge produces different responses on two different PUFs?

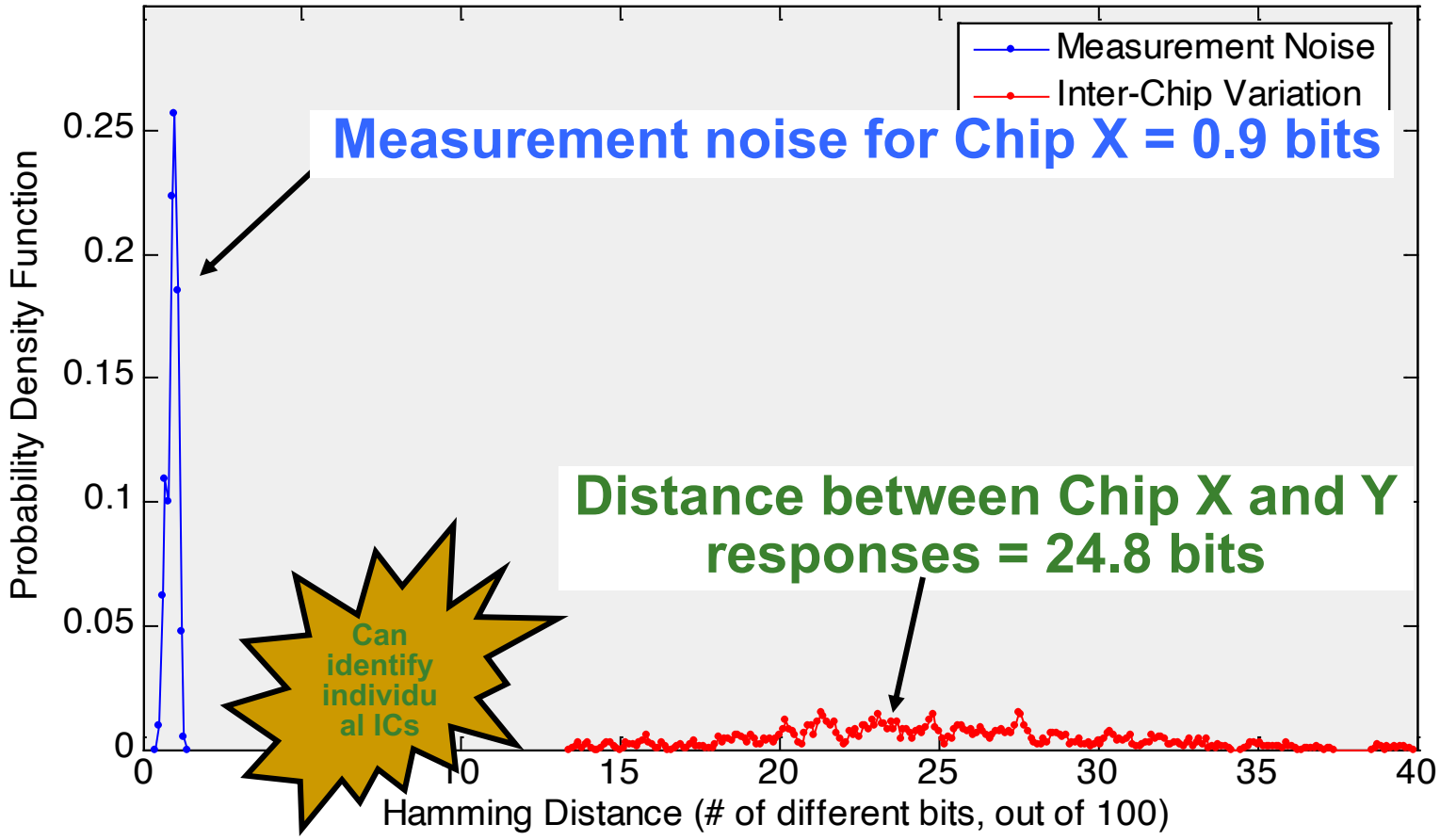
Reliability

– What is the probability that a PUF output for a challenge changes with temperature?

– With voltage variation?

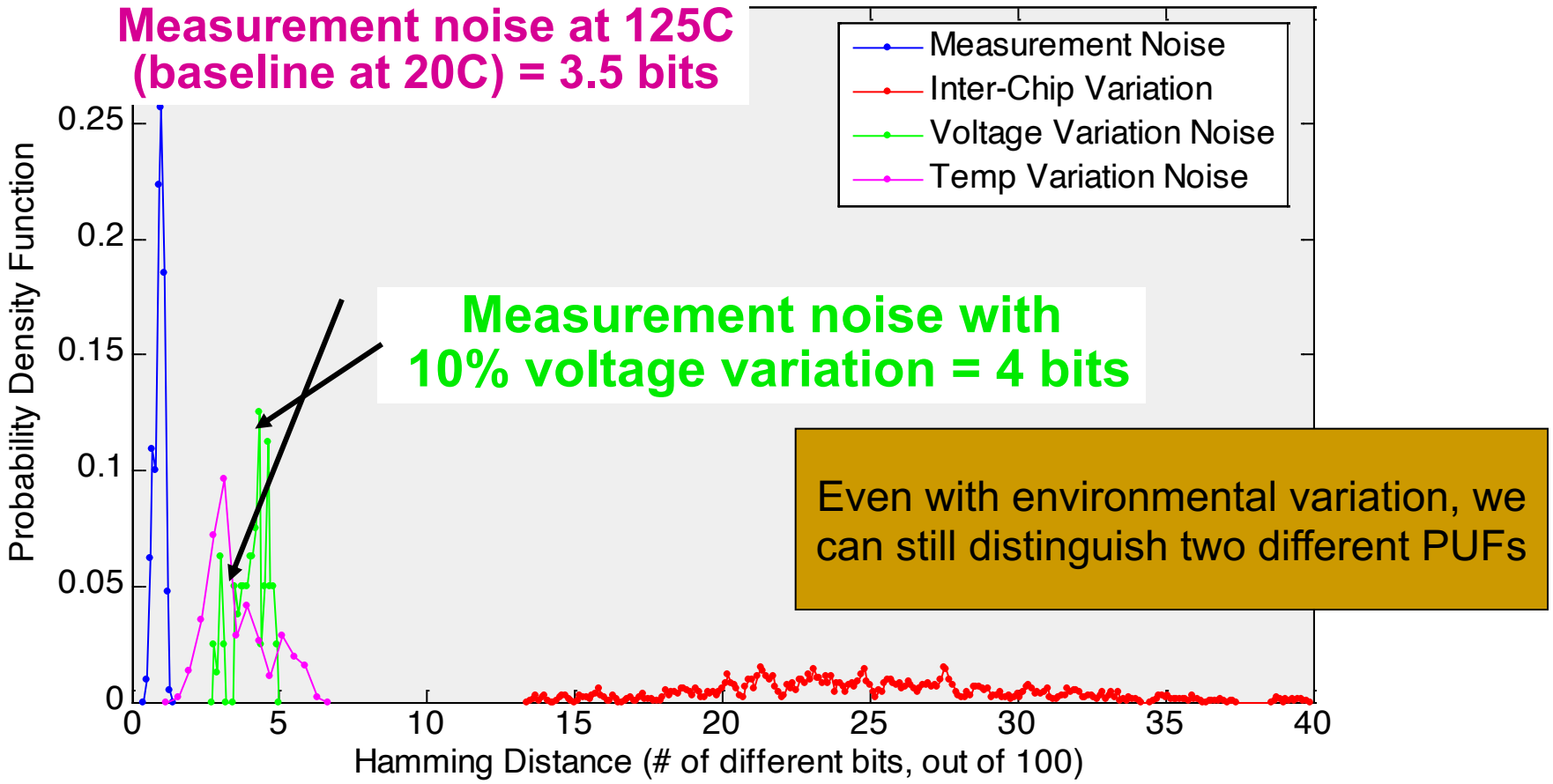
Inter-Chip Variation

- Apply random challenges and observe 100 response bits



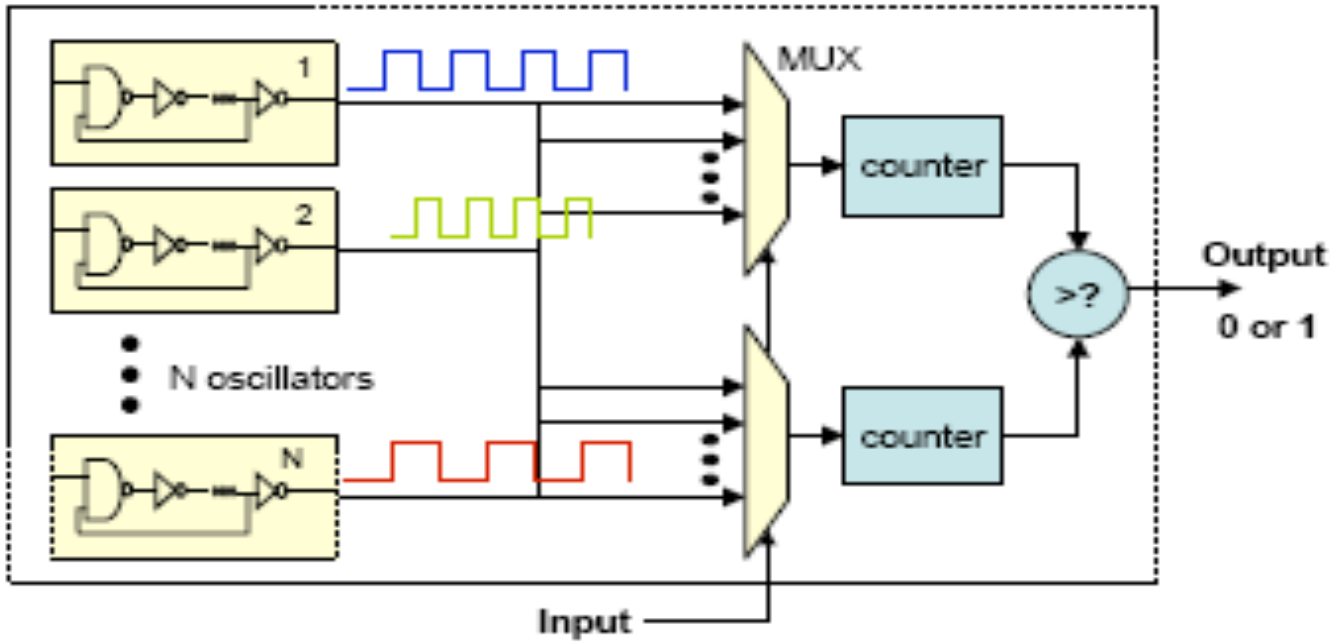
Environmental Variations

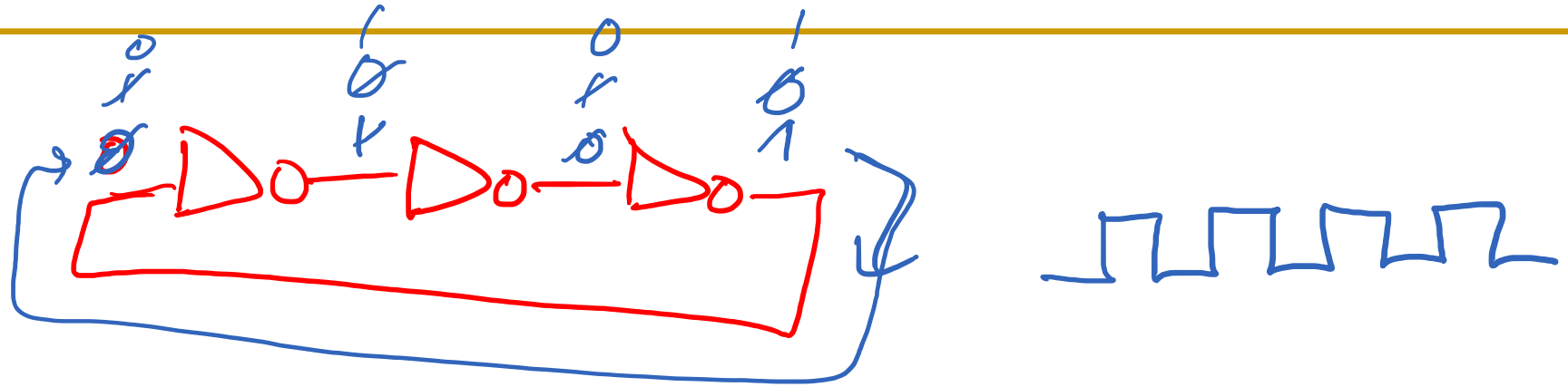
- What happens if we change voltage and temperature?



Ring-Oscillator (RO) PUF

- The structure relies on delay loops and counters instead of MUX and arbiters
- Better results on FPGA – more stable





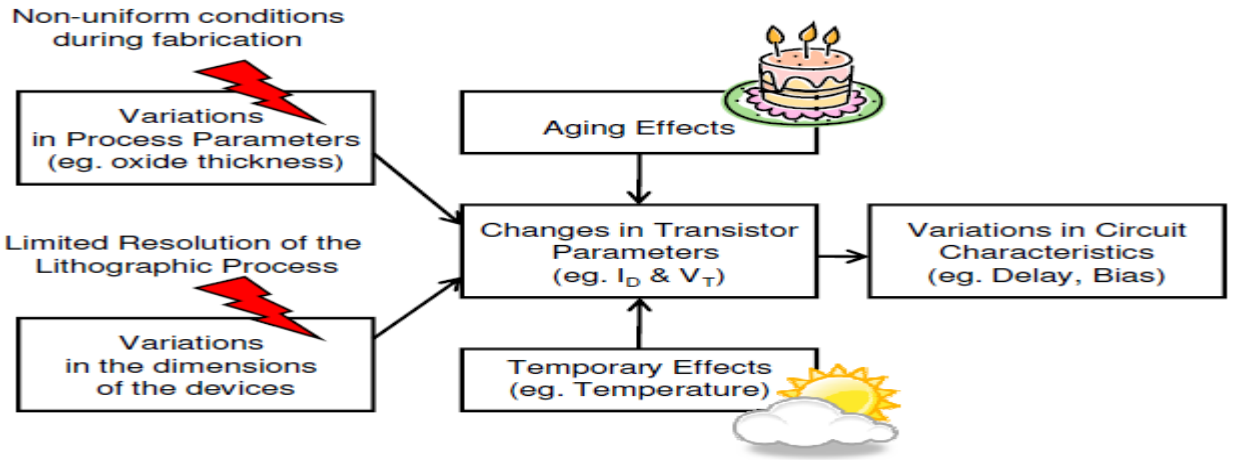
Ring Oscillator

RO PUFs (cont'd)

- Easy to duplicate a ring oscillator and make sure the oscillators are identical
  - Much easier than ensuring the racing paths with equal path segments
- How many bits can we generate from the scheme in the previous page?
  - There are N(N-1)/2 distinct pairs, but the entropy is significantly smaller: $\log_2(N!)$
  - E.g., 35 ROs can produce 133 bits, 128 ROs can produce 716, and 1024 ROs can produce 8769

Consider the following minimal example, given three ROs: $RO_A.f < RO_B.f$ and $RO_B.f < RO_C.f$ implicates $RO_A.f < RO_C.f$. The total PUF entropy is only $log_2(N!)$ bit as there are $N!$ ways to sort the frequency values.

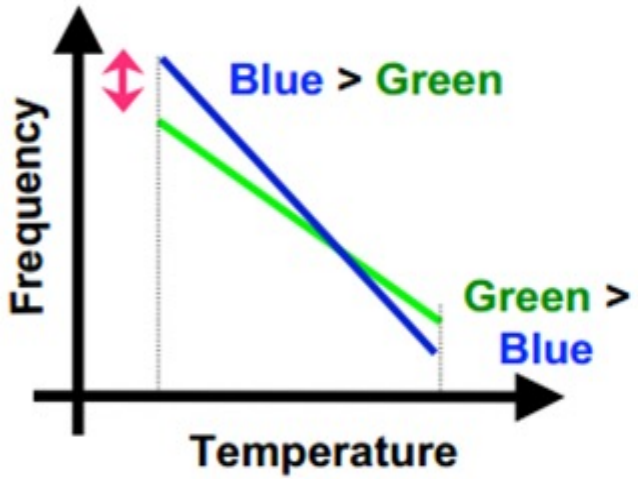
Reliability of RO PUFS



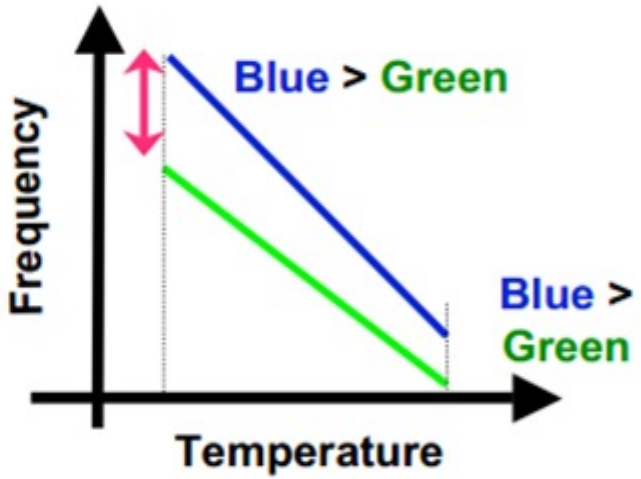
- Two types of reliability issues:
- Aging:
  - Negative Bias Temperature Instability
  - Hot Carrier Injection (HCI)
  - Temp Dependent Dielectric Breakdown
  - Interconnect Failure
- Temperature
  - Slows down the device

Reliability Enhancement

- Environmental changes have a large impact on the freq. (and even relative ones)



(a) Frequencies are close



(b) Frequencies are far apart

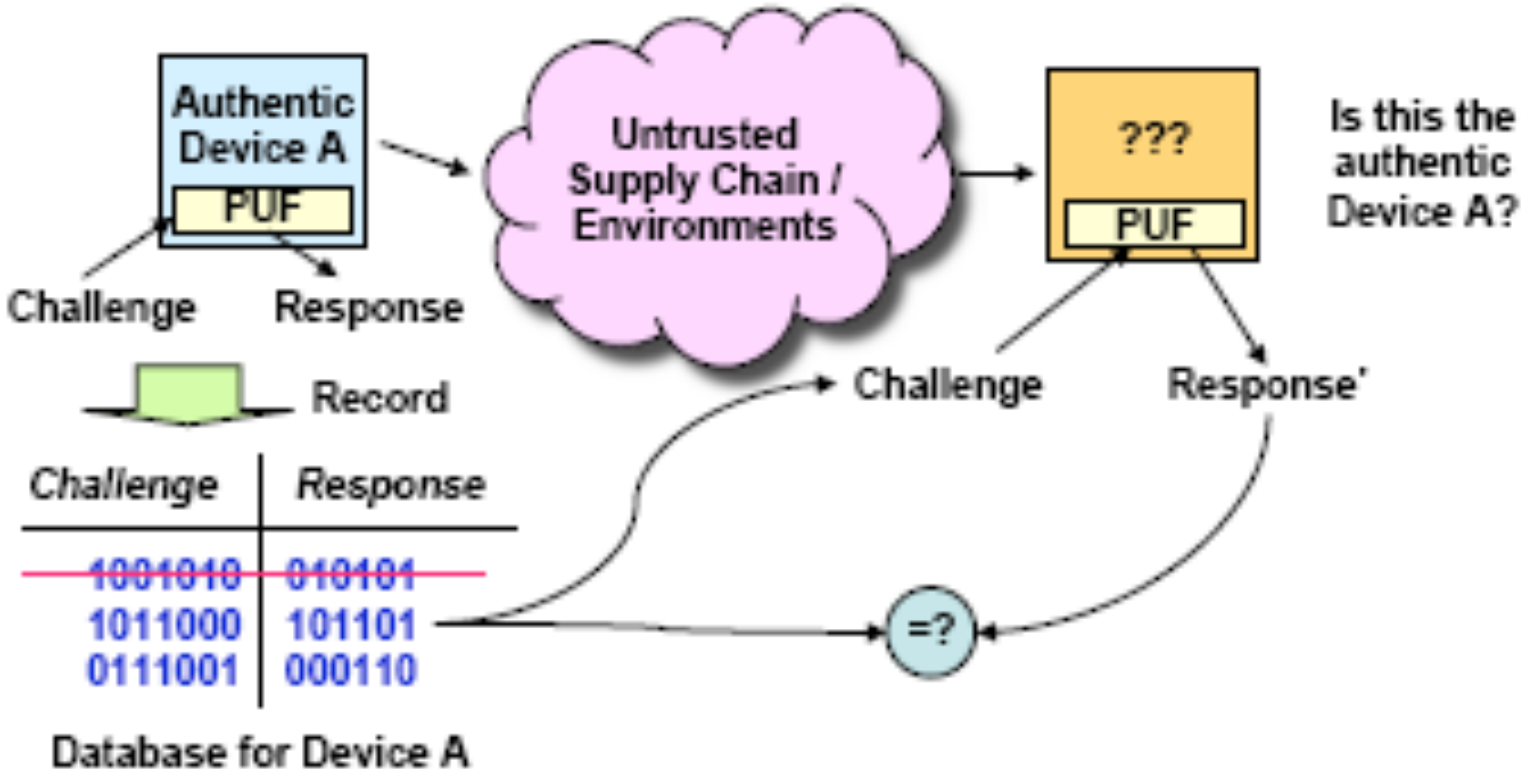
RO PUFs

- ROs whose frequencies are far are more stable than the ones with closer frequencies
  - Possible advantage: do not use all pairs, but only the stable ones
  - It is easy to watch the distance in the counter and pick the very different ones.
    - Can be done during enrollment

- RO PUF allows an easier implementation for both ASICs and FPGAs.
- The **Arbiter** PUF is appropriate for resource constrained platforms such as RFIDs and the **RO PUF** is better for use in FPGAs and in secure processor design.

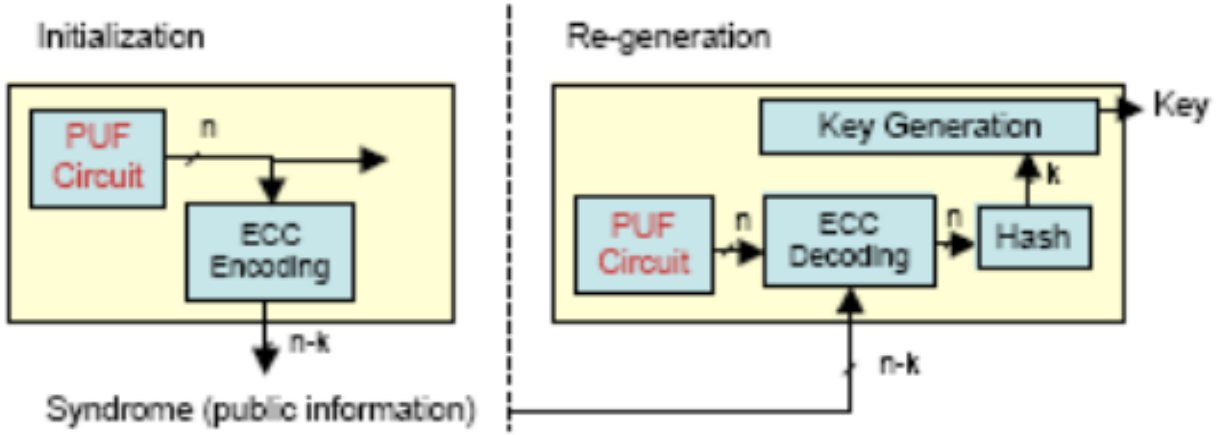
Applications – Authentication

- Same challenges should not be used to prevent the man-in-the-middle attacks



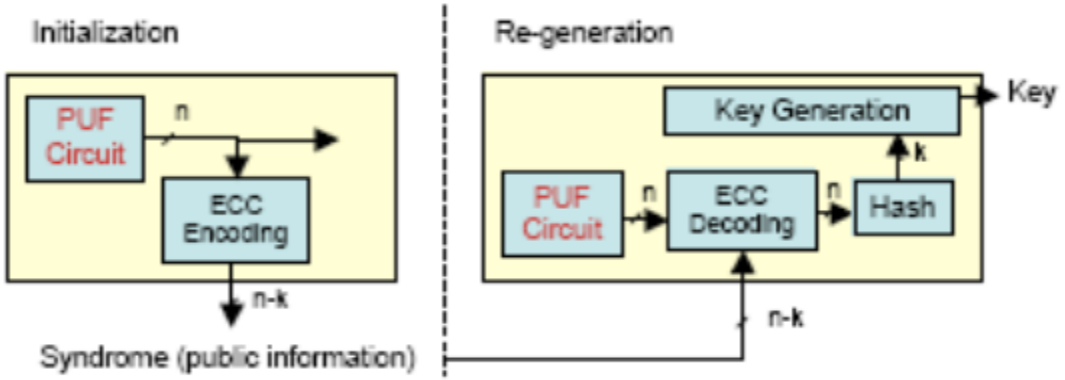
Application – Cryptographic Key Generation

- The unstability is a problem
- Some crypto protocols (e.g., RSA) require specific mathematical properties that random numbers generated by PUFs do not have
- How can we use PUFs to generate crypto keys?
  - Error correction process: initialization and regeneration
  - There should be a one-way function that can generate the key from the PUF output



Crypto Key Generation

- Initialization: a PUF output is generated and error correcting code (e.g., BCH) computes the syndrome (public info)
- Regeneration: PUF uses the syndrome from the initial phase to correct changes in the output
- Clearly, the syndrome reveals information about the circuit output and introduces vulnerabilities



Experiments with RO PUFs

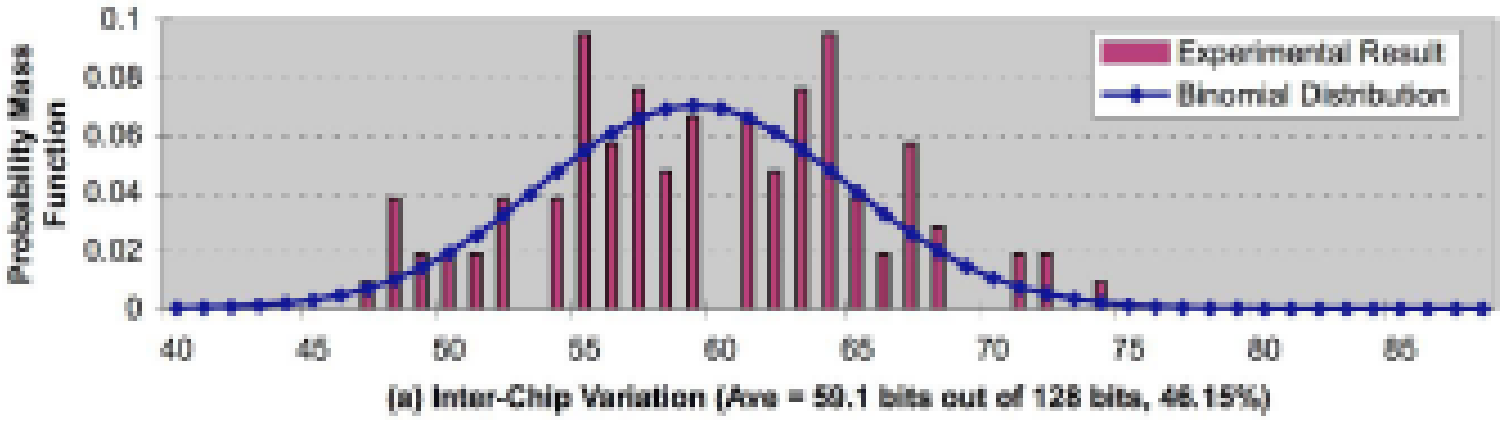
- Experiments done on 15 Xilinx Virtex4 LX25 FPGA (90nm)
- They placed 1024 ROs in each FPGA as a 16-by-64 array
- Each RO consisted of 5 INVs and 1 AND, implemented using look-up tables
- The goal is to know if the PUF outputs are unique (for security) and reproducible (for reliability and security)

Reliability and Security Metrics

- *Inter-chip variation*: How many PUF output bits are different between PUF A and PUF B? This is a measure of uniqueness. If the PUF produces uniformly distributed independent random bits, the inter-chip variation should be 50% on average.
- *Intra-chip (environmental) variation*: How many PUF output bits change when re-generated again from a single PUF with or without environmental changes? This indicates the *reproducibility* of the PUF outputs. Ideally, the intra-chip variation should be 0%.

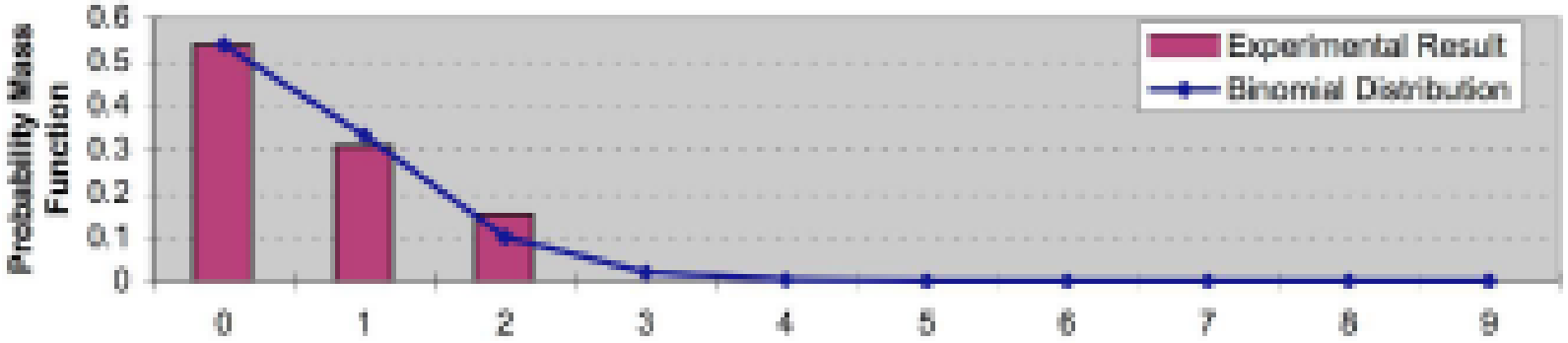
The Probability Distribution for Inter-chip Variations

- 128 bits are produced from each PUF
- x-axis: number of PUF o/p bits different b/w two FPGAs; y-axis: probability
- Purple bars show the results from 105 pair-wise comparisons
- Blue lines show a binomial distribution with fitted parameters (n=128, p =0.4615)
- Average inter-chip variations 0.4615 ~ 0.5



The Probability Distribution for Intra-chip Variations

- PUF responses are generated at two different conditions and compared
- Changing the temperature from 20°C to 120°C and the core voltage from 1.2 to 1.08 altered the PUF o/p by ~0.6 bits (0.47%)
- Intra-chip variations is much lower than inter-chip – the PUF o/p did not change from small to moderate



(b) Intra-Chip Var. under the Worst-Case Env. Change (20C 1.2V vs. 120C 1.08V)
(Avg = 0.61 bits out of 128 bits, 0.48%)

Configurable Ring Oscillator

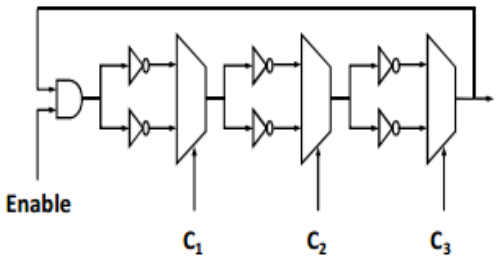


Fig. 3(a)

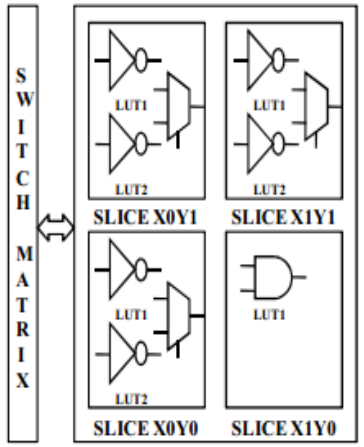


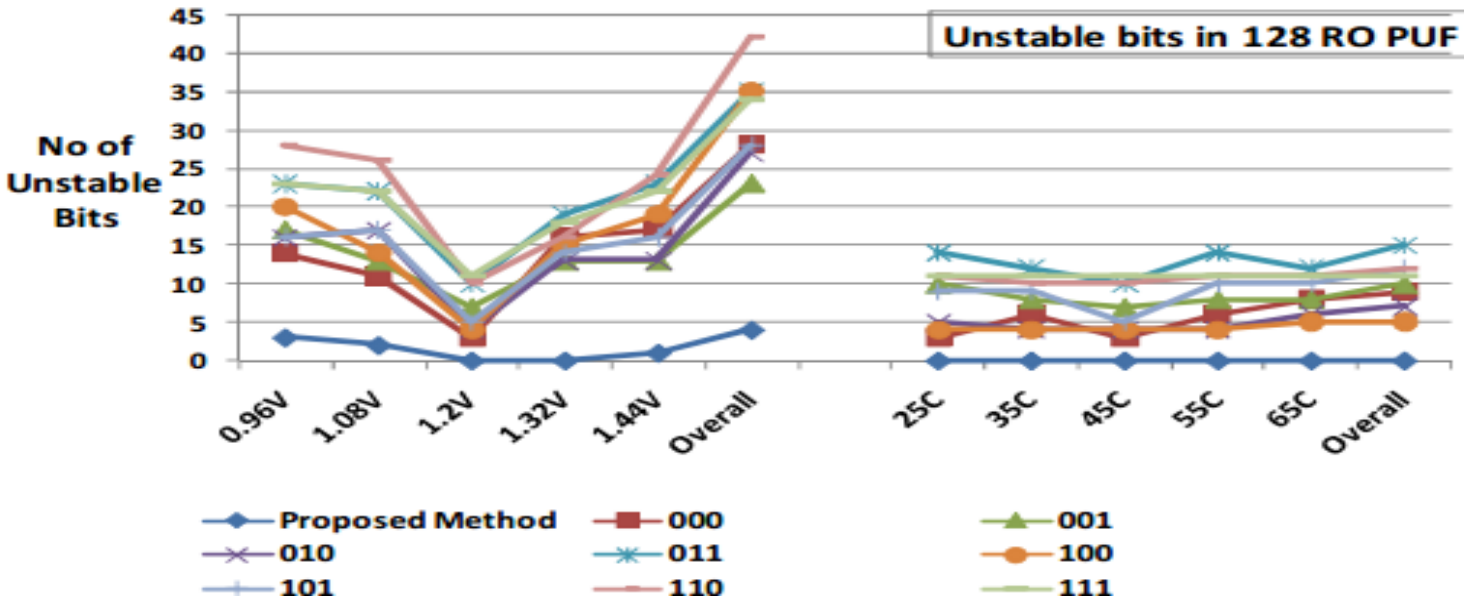
Fig. 3(b)

Table 1. Frequency differences in a configurable RO pair

$c_1c_2c_3$	Frequency of ROs in CLB i	Frequency of ROs in CLB j	Δf
000	f_0	f'_0	$\lvert f_0 - f'_0 \rvert$
001	f_1	f'_1	$\lvert f_1 - f'_1 \rvert$
010	f_2	f'_2	$\lvert f_2 - f'_2 \rvert$
011	f_3	f'_3	$\lvert f_3 - f'_3 \rvert$
100	f_4	f'_4	$\lvert f_4 - f'_4 \rvert$
101	f_5	f'_5	$\lvert f_5 - f'_5 \rvert$
110	f_6	f'_6	$\lvert f_6 - f'_6 \rvert$
111	f_7	f'_7	$\lvert f_7 - f'_7 \rvert$

- The pair which has the maximum difference in frequency in CRO is selected.

Configurable Ring Oscillator



- Higher difference in frequency will ensure higher reliability
- Redundancy

True Random Number Generator

Random Numbers in Cryptography

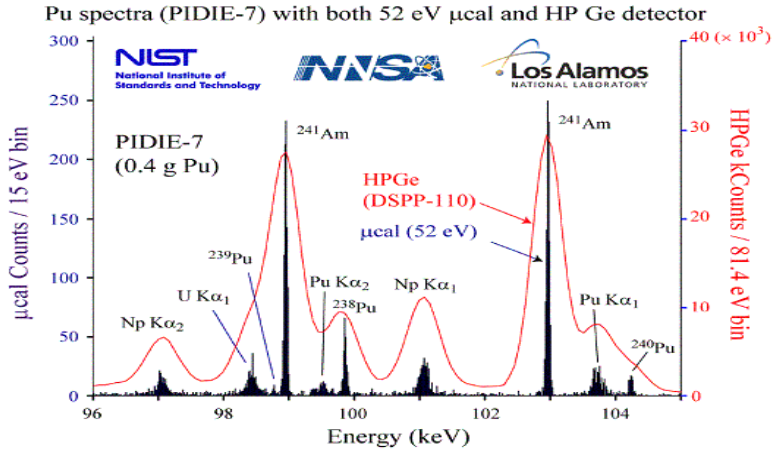
- The keystream in the one-time pad
- The secret key in the DES encryption
- The prime numbers p, q in the RSA encryption
- Session keys
- The private key in digital signature algorithm (DSA)
- The initialization vectors (IVs) used in ciphers

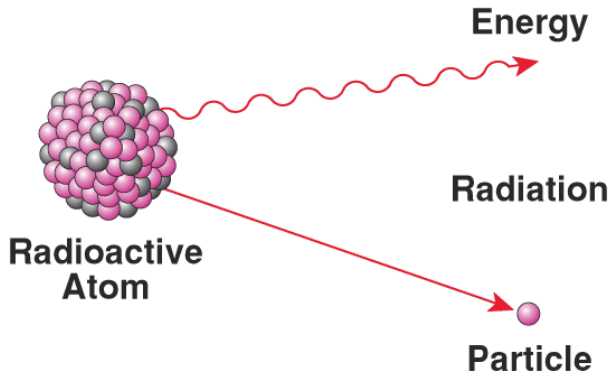
Pseudo-random Number Generator

- **Pseudo-random number generator:**
  - A polynomial-time computable function f (x) that expands a short random string x into a long string f (x) that appears random
- **Not truly random in that:**
  - Deterministic algorithm
  - Dependent on initial values (seed)
- **Objectives**
  - Fast
  - Secure

Sources

- The only truly random number sources are those related to physical phenomena such as **the rate of radioactive decay** of an element or the **thermal noise** of a semiconductor.





- Randomness is bound to natural phenomena. It is impossible to algorithmically generate truly random numbers.

Microcalorimeter (black) and high-purity germanium (red) spectra of a mixture of plutonium isotopes. Minimal thermal noise is achieved at 100 mK. High sensitivity is due to use of a superconducting quantum interference device.

https://www.aps.org/units/fps/newsletters/2006/july/article6.html

Good TRNG Design

- **Entropy Source:**
  - Randomness present in physical processes such as thermal and shot noise in circuits, brownian motion, or nuclear decay.
- **Harvesting Mechanism:**
  - The mechanism that does not disturb the physical process but collects as much entropy as possible.
- **Post-Processing (optional):**
  - Applied to mask imperfections in entropy sources or harvesting mechanism or to provide tolerance in the presence of environmental changes and tampering.

Shot noise, the time-dependent fluctuations in electrical current caused by the discreteness of the electron charge, is well known to occur in solid-state devices.

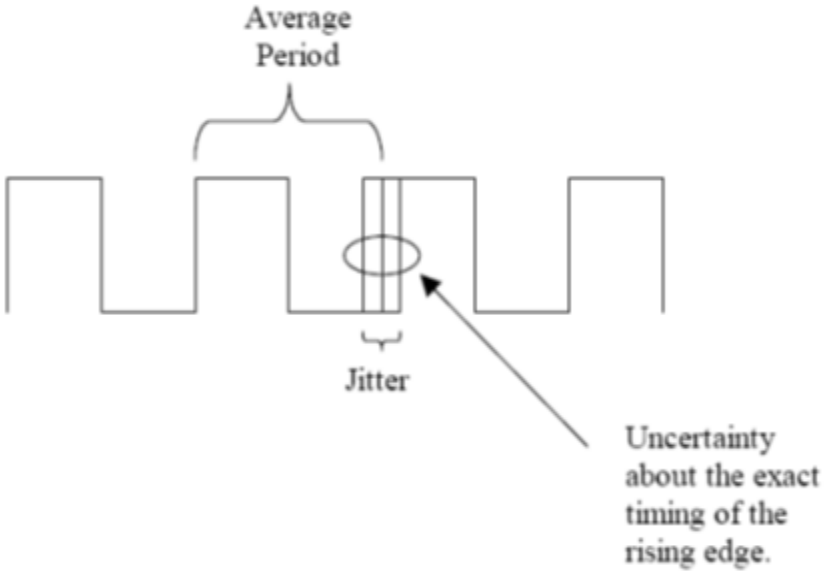
Set of Requirements

- The Design Should be purely digital
- The harvesting mechanism should be simple.
  - The unpredictability of the TRNG should not be based on the complexity of the harvesting mechanism, but only on the unpredictability of the entropy source.
- No correction circuits are allowed
- Compact and efficient design (high throughput per area and energy spent).
- The design should be sufficiently simple to allow rigorous analysis.

Method : Clock Jitter

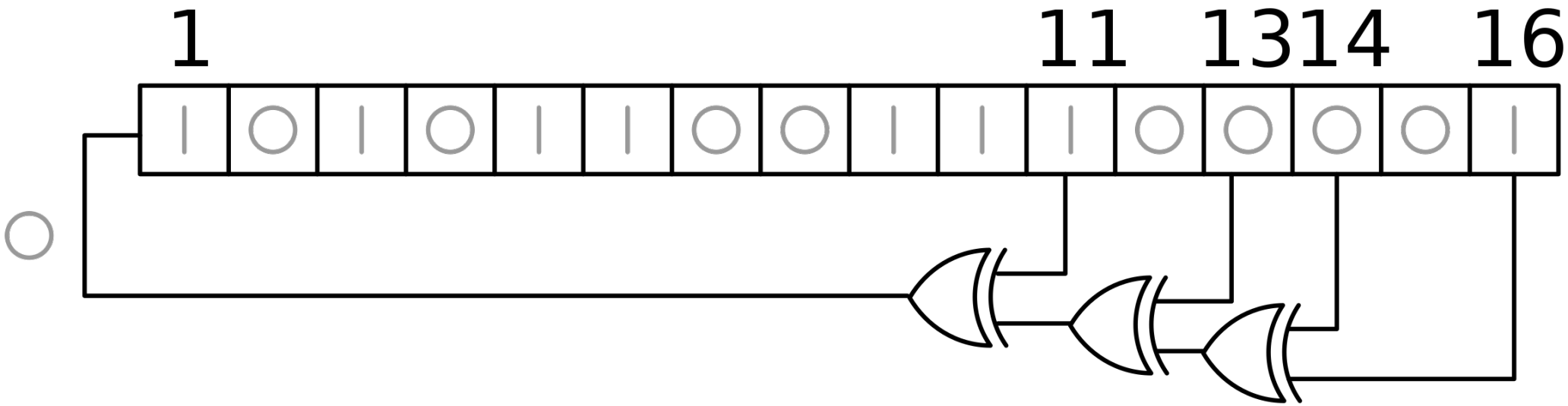
- Jitter is variations in the significant instants of a clock
- Jitter is nondeterministic (random)

- **Sources of Jitter:**
  - Semiconductor noise
  - Cross-talk
  - Power supply variations
  - Electromagnetic fields



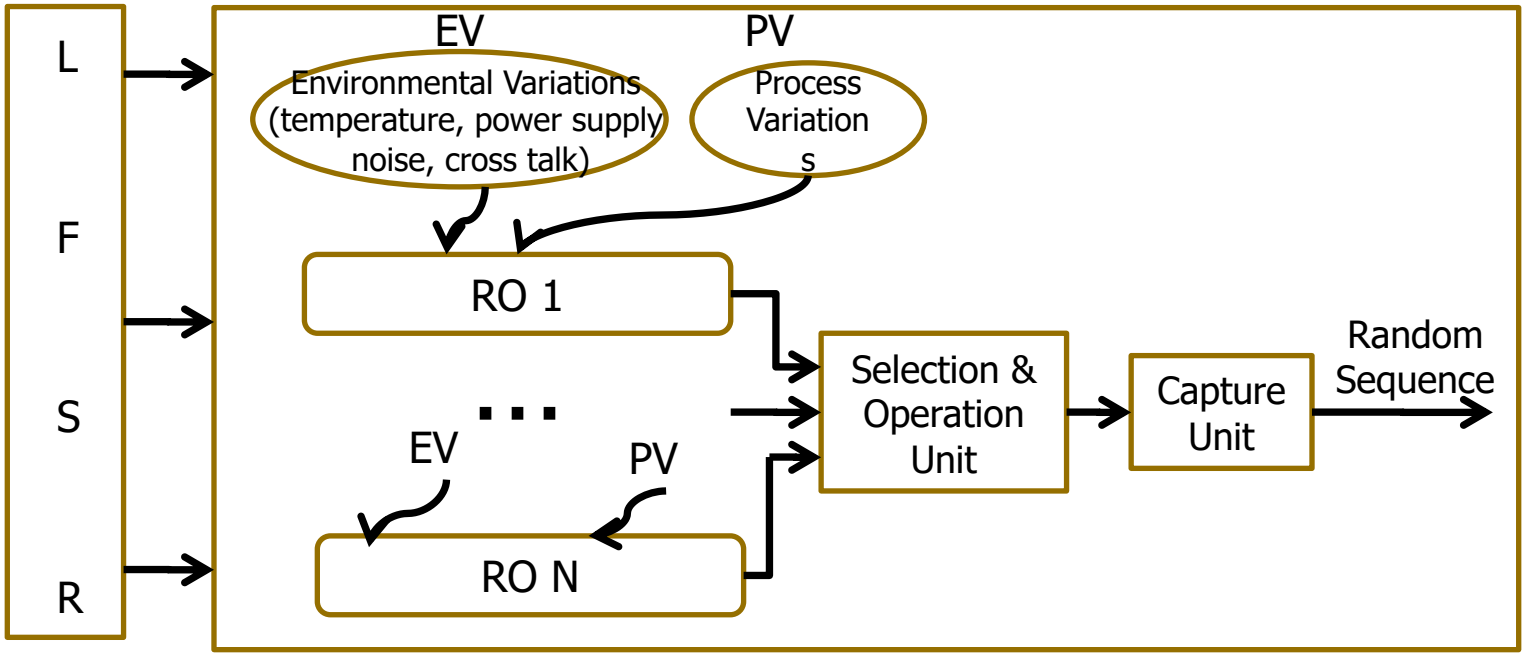
LFSR

- Linear Feedback Shift Register - a shift register whose input bit is a linear function of its previous state



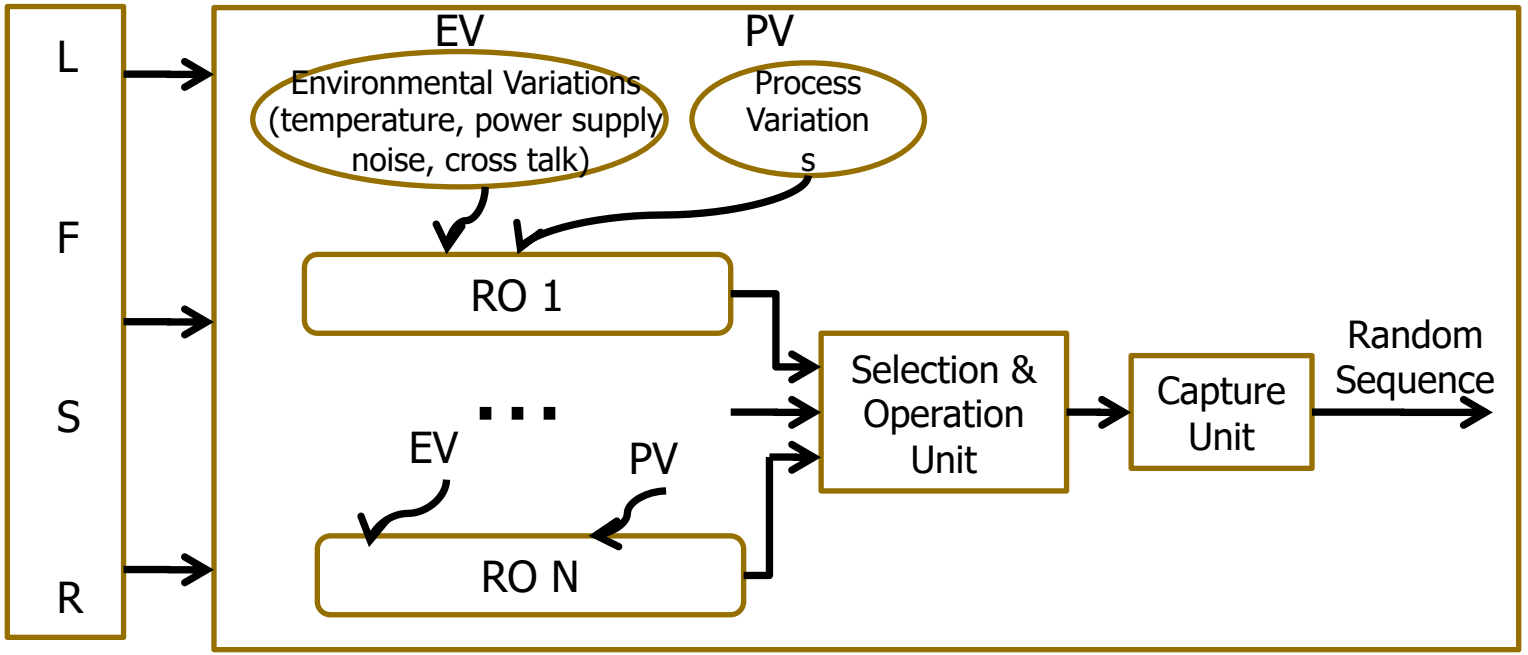
TRNG Structure

- **LFSR**: Generate random patterns, causing random switching noise



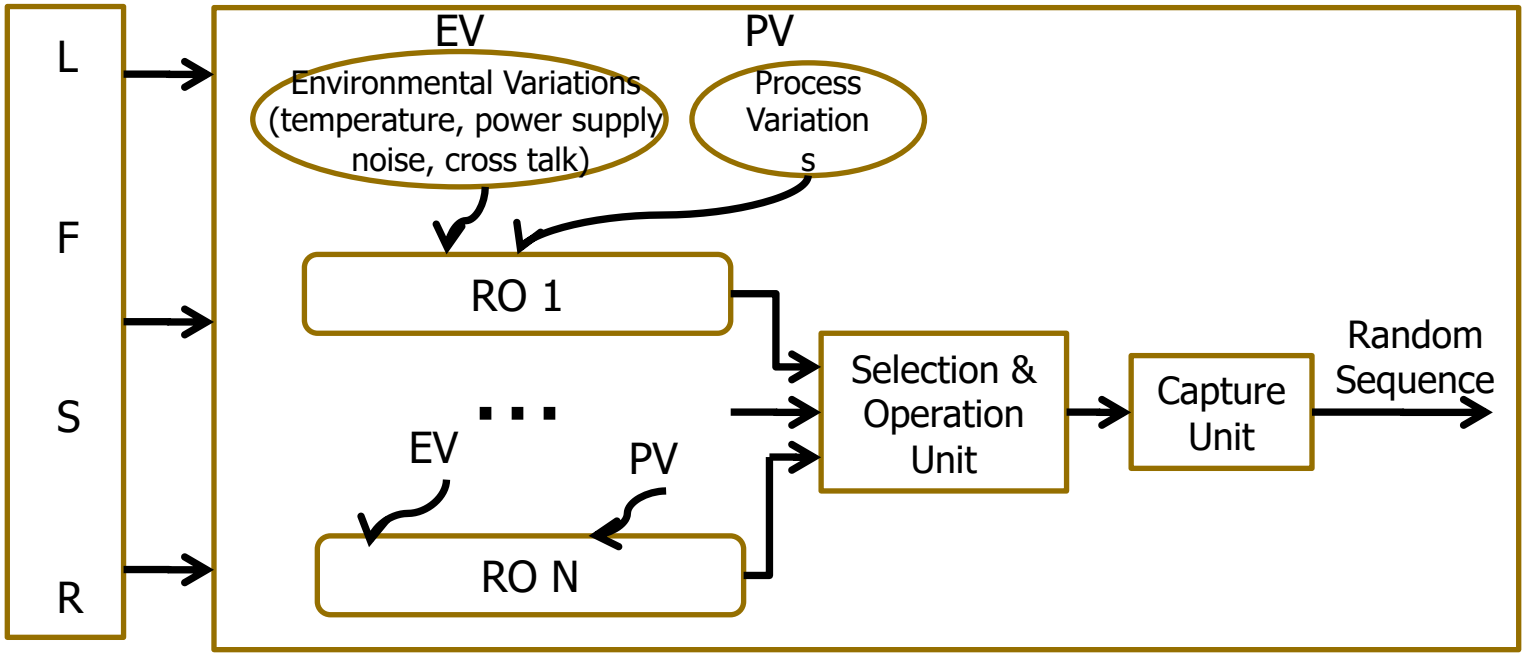
TRNG Structure

- **Ring Oscillators**
  - Process variations & environmental variations
  - Random phase jitter



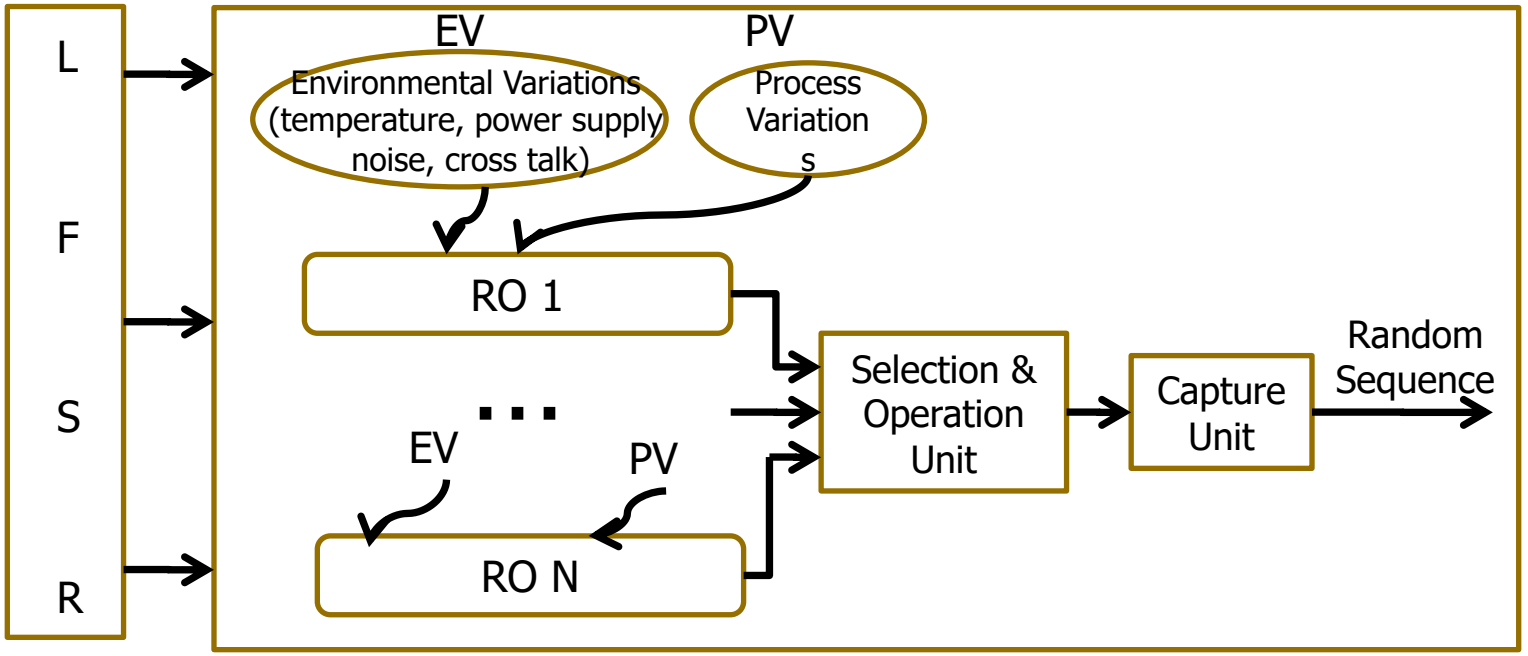
TRNG Structure

- **Selection & Operation Unit:** The random phase of ring oscillators could be translated into digital values by this unit, such as XOR operation

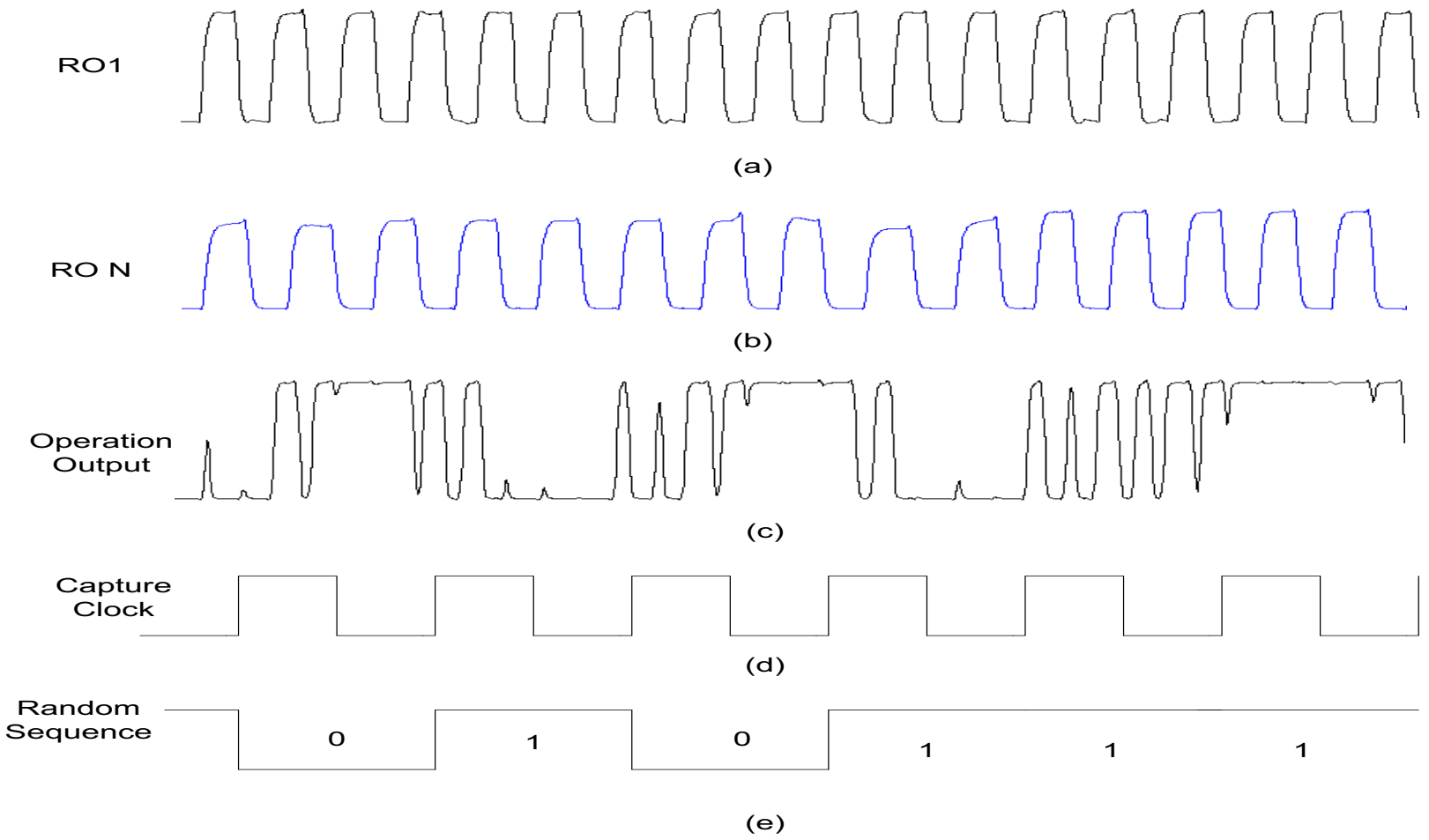


TRNG Structure

- **Capture Unit:** Make sure the digital value is sampled with the frequency of the required true random number.



TRNG Output


RO1
(a)
RO N
(b)
Operation Output
(c)
Capture Clock
(d)
Random Sequence
0
1
0
1
1
1
(e)

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- [1]Suh, G.E., Devadas, S.: Physical unclonable functions for device authentication and secret key generation. In: Design Automation Conference, pp. 9{14. ACM Press, New York, NY, USA (2007)
- [2]Gassend, B., Lim, D., Clarke, D., van Dijk, M., Devadas, S.: Identication and au-thentication of integrated circuits: Research articles. Concurr. Comput. : Pract. Exper.16(11), 1077-1098.
- [3]Gassend, B., Clarke, D., van Dijk, M., Devadas, S.: Controlled physical random functions. In: ACSAC '02: Proceedings of the 18th Annual Computer Security Applications Conference, p. 149. IEEE Computer Society, Washington, DC, USA (2002)
- [4]B. Gassend, D. Clarke, M. van Dijk, and S. Devadas. Silicon physical random functions. In Proceedings of the Computer and Communication Security Conference , November 2002.
- [5] Dinesh Ganta, Vignesh Vivekraja, Kanu Priya and Leyla Nazhandali, “A Highly Stable Leakage-Based Silicon Physical Unclonable Functions”

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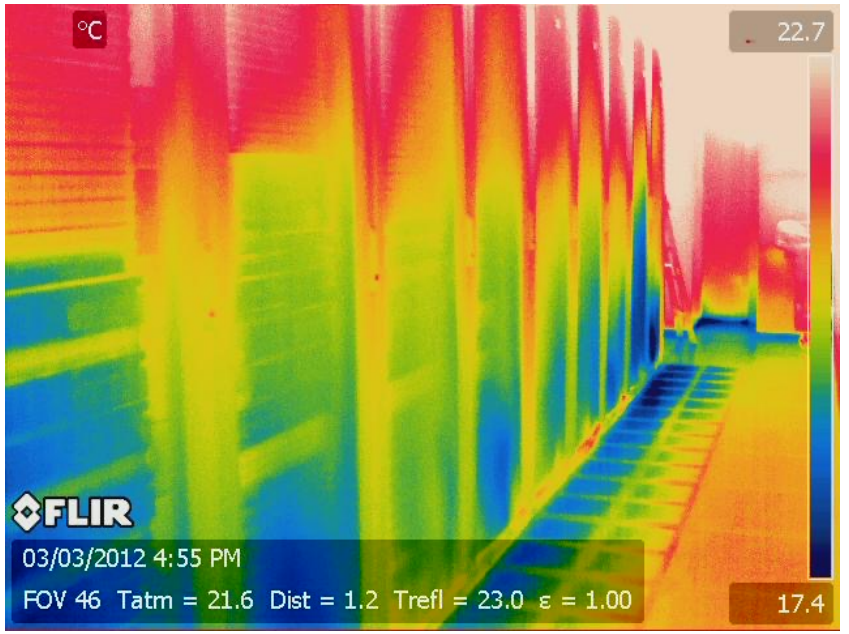
- [6] A. Maiti and P. Schaumont, “Improved ring oscillator puf: An fpga-friendly secure primitive,” J. Cryptology, vol. 24, no. 2, pp. 375–397.,2011.
- [7] B. Sunar, W. J. Martin, D. R. Stinson. A Provably Secure True Random Number Generator with Built-in Tolerance to Active Attacks. IEEE Transactions on Computers, vol 58, no 1, pages 109-119, January 2007.

More on PUF Applications

Motivation: Securely Sensing without Key

- Physical features should be closely monitored
  - The temperature of data center, Facebook, Google, Amazon, etc



Motivation: Securely Sensing without Key

- Physical features should be closely monitored
  - The temperature of data center, Facebook, Google, Amazon, etc

- Some physical features might be meaningful for security/privacy
  - Relative location between bank cards and automated teller machines (ATMs), card (not) present withdrawal

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- Physical features should be closely monitored
  - The temperature of data center, Facebook, Google, Amazon, etc
- Some physical features might be meaningful for security/privacy
  - Relative location between bank cards and automated teller machines (ATMs), card (not) present withdrawal
- Some physical features are hard to sense but favoring many applications
  - Digital rights management, physically/irreversibly canceling membership?

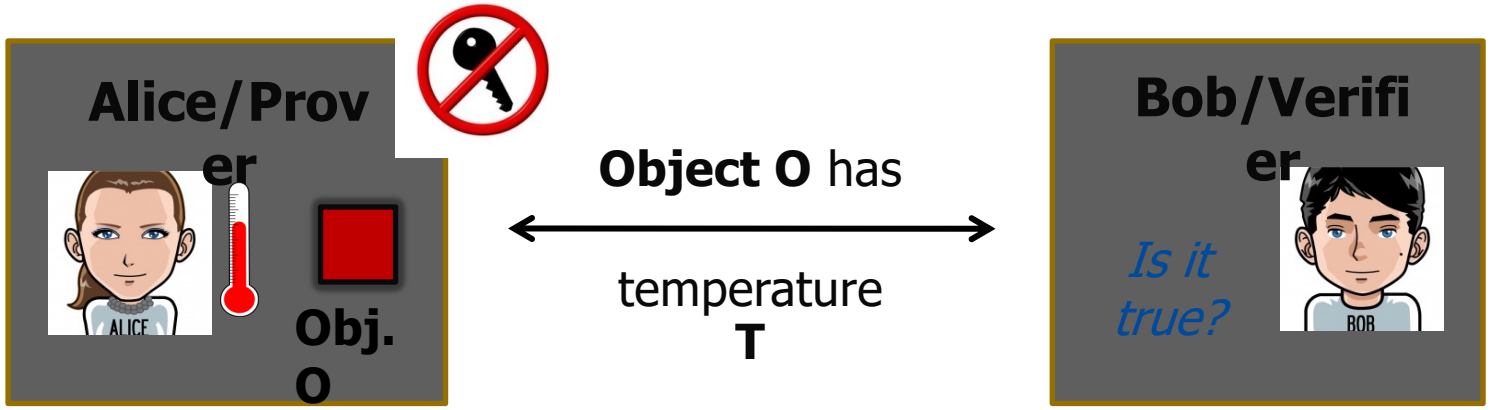
- Secure sensors are needed:
  - Operation safety, secrecy of sensitive data

Key Is a Target

- Modern security protocols are commonly based on secret keys.
- A robust key enhances the robustness of security systems, but also announces itself as an interested target for attackers. [1]

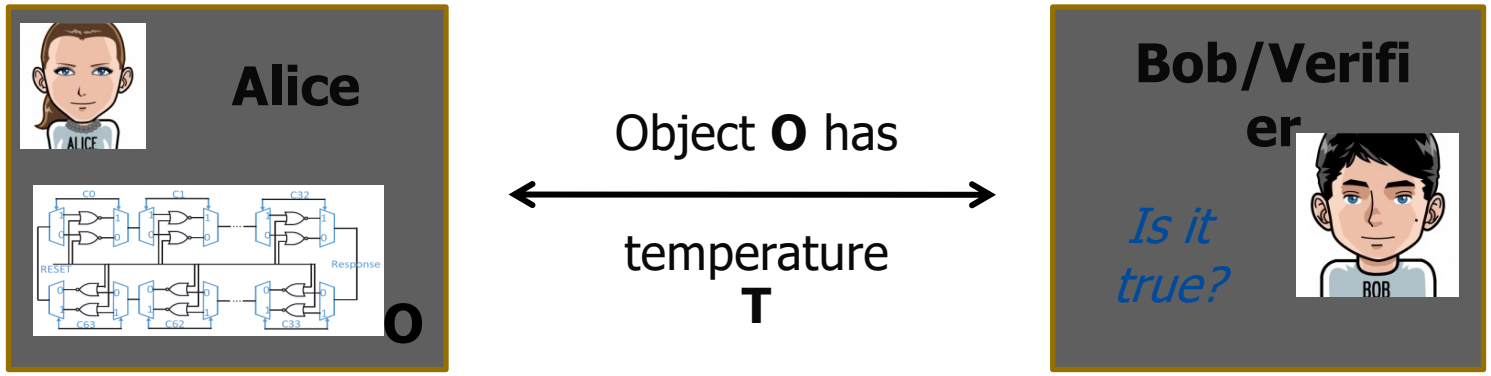
[1] Rivest, Ronald L. Illegitimi non carborundum. CRYPTO (2011).

Virtual Proofs of Temperature
(Or: Keyless Temperature Sensors)



- Alice wants to prove to Bob that
  - a certain **object O**
  - is at temperature **T**
  - at the time of the execution of the VP
- **Classical approach:** Secure sensors with key known to Bob…
  - Buf, of course, we want no keys…

VPs of Temperature via Noise Sensitivity



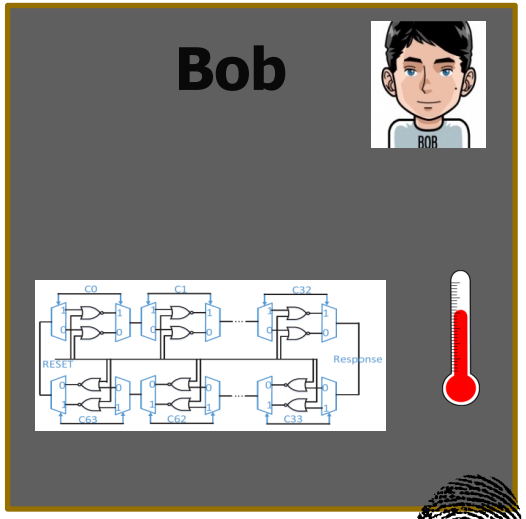
- **Key Idea:** Use a ***temperature-sensitive Strong PUF*** as **Object O**
  - ie., an integrated circuit **(IC)** / **PUF** whose output **intentionally** depends upon the ambient temperature **T**
  - Output of the IC/PUF to Bob‘s random challenges proves temperature

VP of Temperature $T_i \in \{T_1, \ldots, T_k\}$

Private set-up phase:

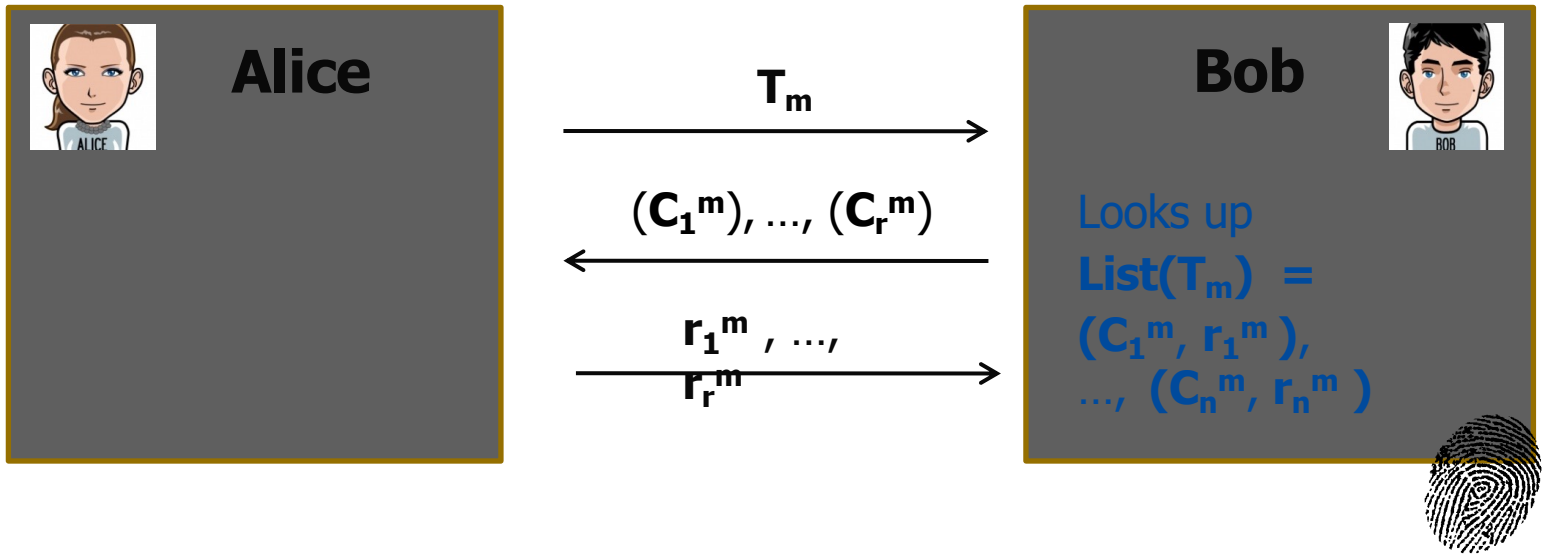
- For each temperature $\mathbf{T_i \in \{T_1, \ldots, T_k\}}$:
  - **Bob** puts the objects $\mathbf{O_1}$ at temperature $\mathbf{T_i}$
    Chooses **n** random **challenges** $\mathbf{C_1^i, \ldots, C_n^i}$
    Measures the **n** resulting **responses**: $\mathbf{r_1^i, \ldots, r_n^i}$
  - **Bob** creates&stores private list $\mathbf{List(T_i)} = (C_1^i, r_1^i), \ldots, (C_n^i, r_n^i)$

VP of Temperature $T_i \in \{T_1, \ldots, T_k\}$



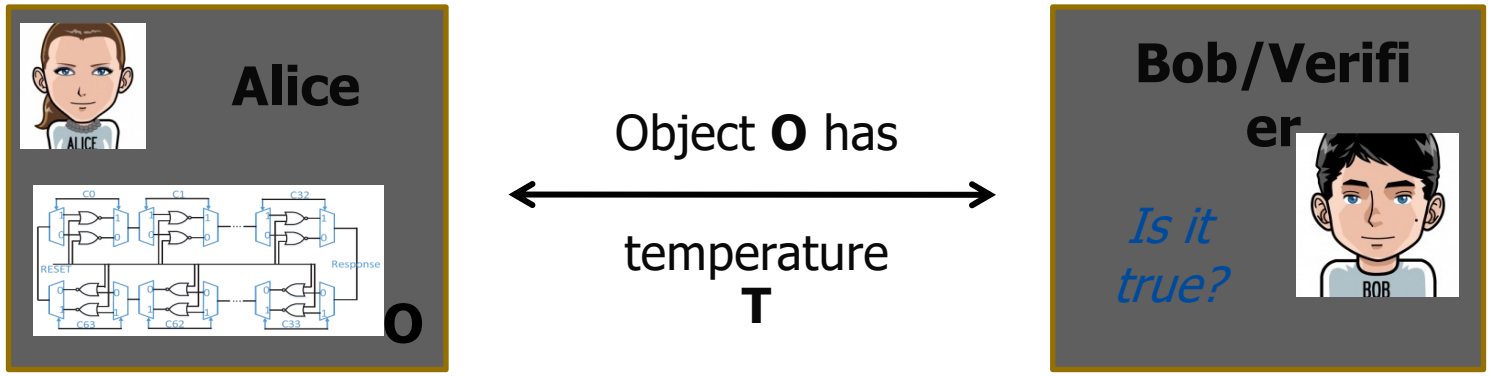
- Set-up phase closes,
  and the objects are transferred to **Alice**
- Some time may pass…
  (time for Alice to attack the system…)
- **VP starts!!**

VP of Temperature $T_i \in \{T_1, \ldots, T_k\}$



- If pre-recorded values l_i^m in the **match** the values that **Alice** sen then **Bob** will **accept** the **VP**

VPs of Temperature via Noise Sensitivity



- Leads to **„keyfree temperature sensors“**
  - Practical outcome of our new theoretical concept!!!
- Temp.-dependent behavior in PUFs usually **unwanted**
  - Turning known weakness of PUF into strength!
- **Again,** all standard properties of PUFs needed
  - Unclonability, no modeling, many challenge-response pairs