Physical Unclonable Function

Yu Bi

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University of Rhode Island

Storage

In traditional methods, secret keys are stored digitally in a nonvolatile memory which is always vulnerable based on hardware implementation and key storage.

Authentication

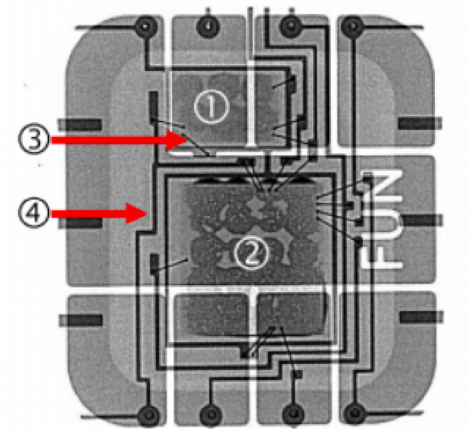
For extremely resource constrained platforms such as RFIDs, even simple cryptographic operations can be too costly.

Attacks

Software-only protection is not enough. Non-volatile memory technologies are vulnerable to invasive attack as secrets always exist in digital form

Attack Model

- **Attacker goals**
  - To get the crypto keys stored in RAM or ROM
  - To learn the secret crypto algorithm used
  - To obtain other information stored into the chip (e.g. PINs)
  - To modify information on the card (e.g. calling card balance)



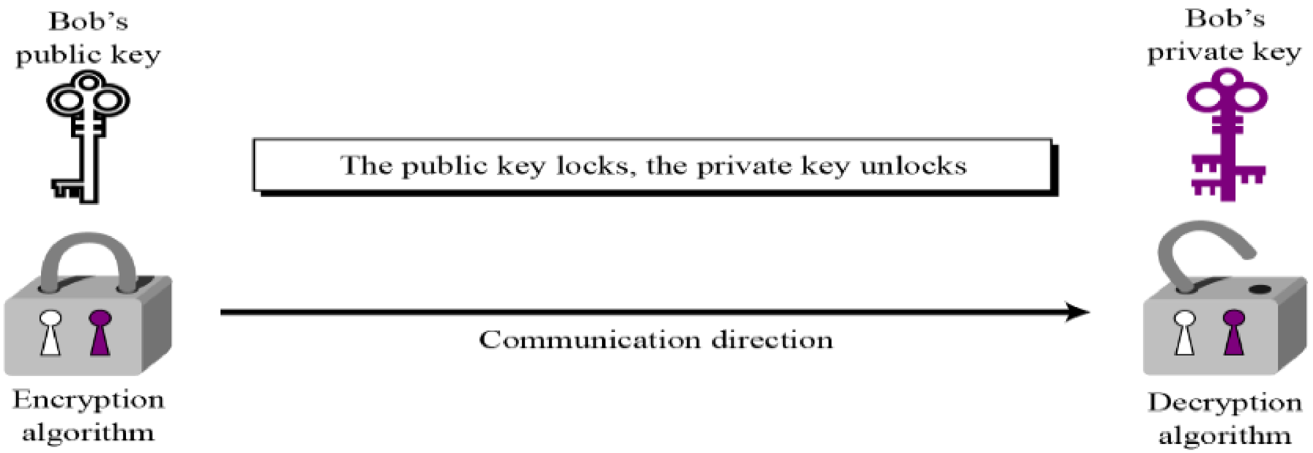
Over $680,000 stolen via a clever man-in-the-middle attack on chip cards in 2011.

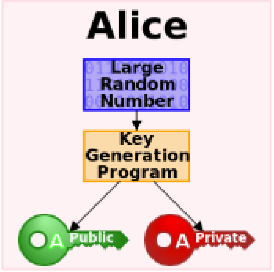
https://arstechnica.com/tech-policy/2015/10/how-a-criminal-ring-defeated-the-secure-chip-and-pin-credit-cards/

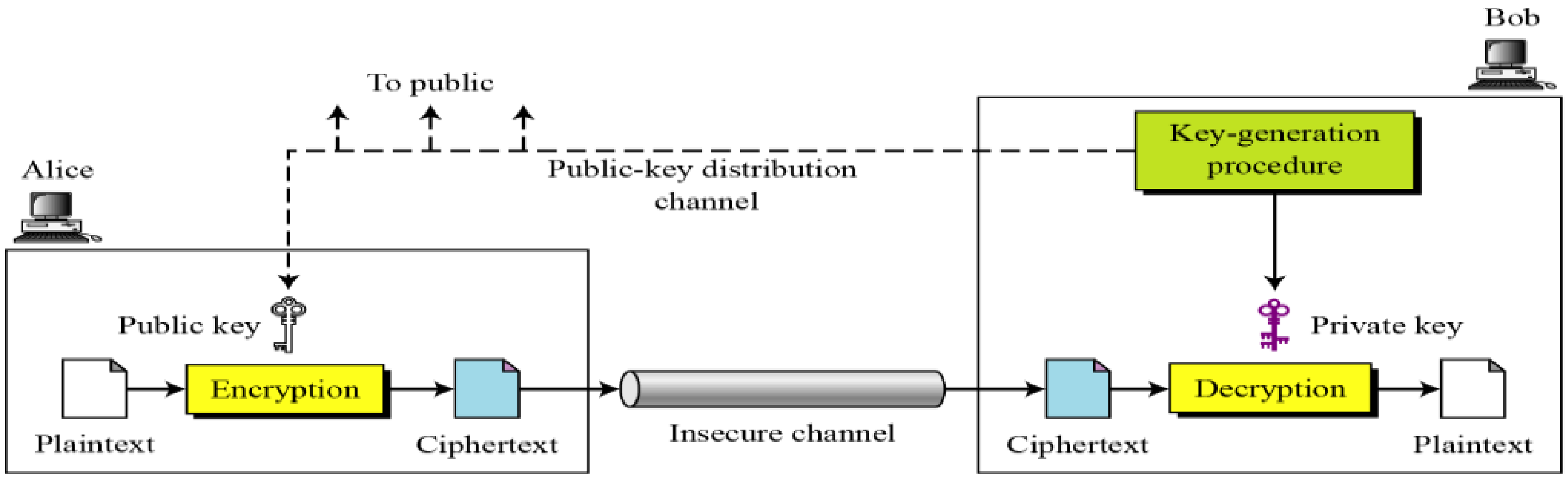
Keys

- Keys are rules used in algorithms to convert a document into a secret document
- Keys are of two types:
  - Symmetric
  - Asymmetric
- A key is symmetric if the same key is used both for encryption and decryption
- A key is asymmetric if different keys are used for encryption and decryption

Asymmetric Security







Asymmetric 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

Challenges

- **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

Solutions

- 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

IBM 4758

Problem:

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

IBM 4758

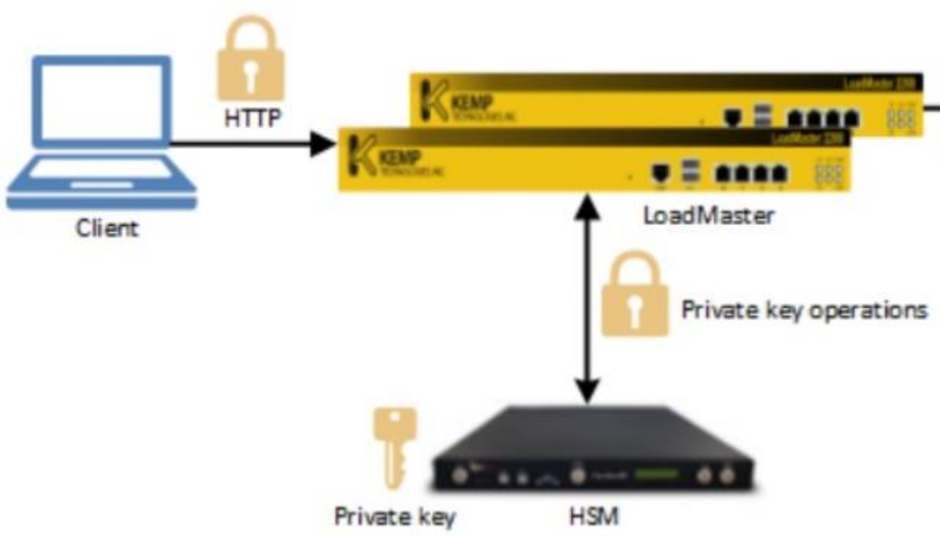
Tamper-proof package containing a secure processor which has a secret key and memory

- Tens of sensors, resistance, temperature, voltage, etc.
- Continually battery-powered

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

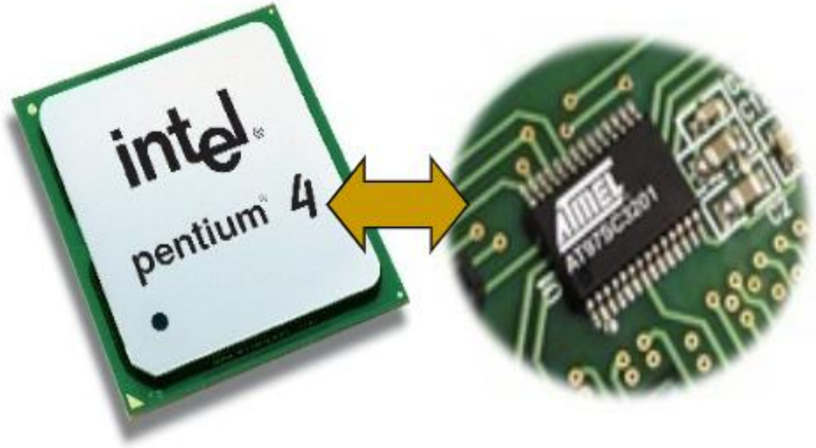
HSM

A **hardware security module** (**HSM**) is a physical computing device that safeguards and manages digital keys for strong authentication and provides crypto processing. These modules traditionally come in the form of a plug-in card or an external device that attaches directly to a computer or network server. - Wikipedia



TPM

A **Trusted Platform Module** (**TPM**) is a specialized chip on an endpoint device that stores RSA encryption keys specific to the host system for hardware authentication. Each TPM chip contains an RSA key pair called the Endorsement Key (EK). -- Wikipedia

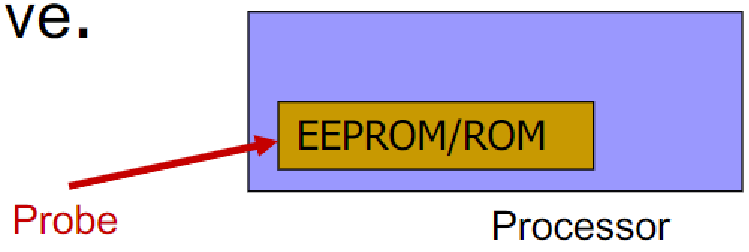


A separate chip (TPM) for security functions

Decrypted “secondary” keys can be read out from the bus

Problem

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



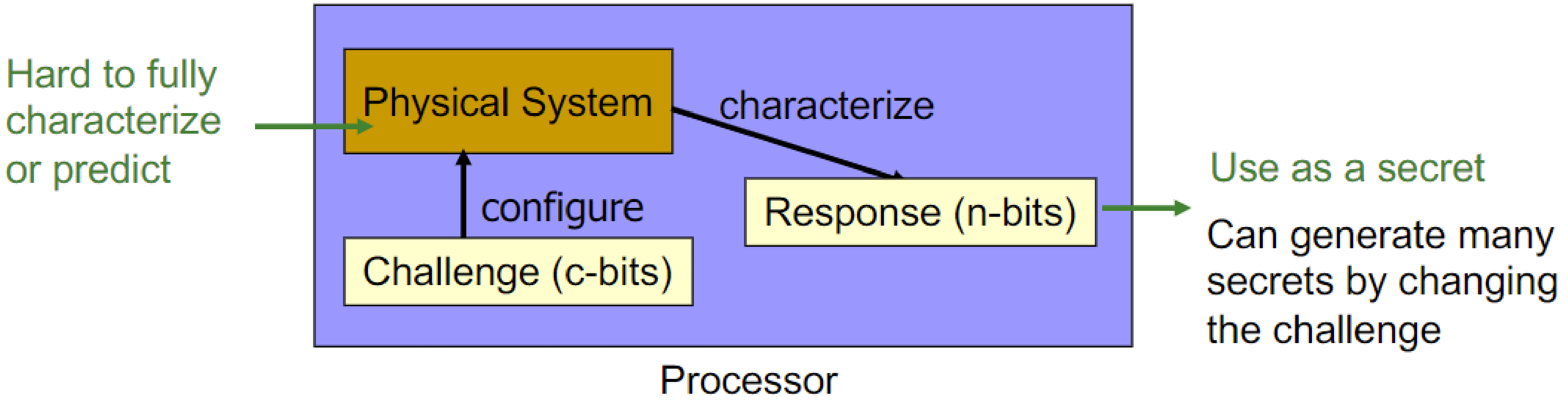
- Adversaries can physically extract secret keys from EEPROM while processor is off
- Trusted party must embed and test secret keys in a secure location
- EEPROM adds additional complexity to manufacturing

Process Variations

- 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

Physical Unclonable 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:

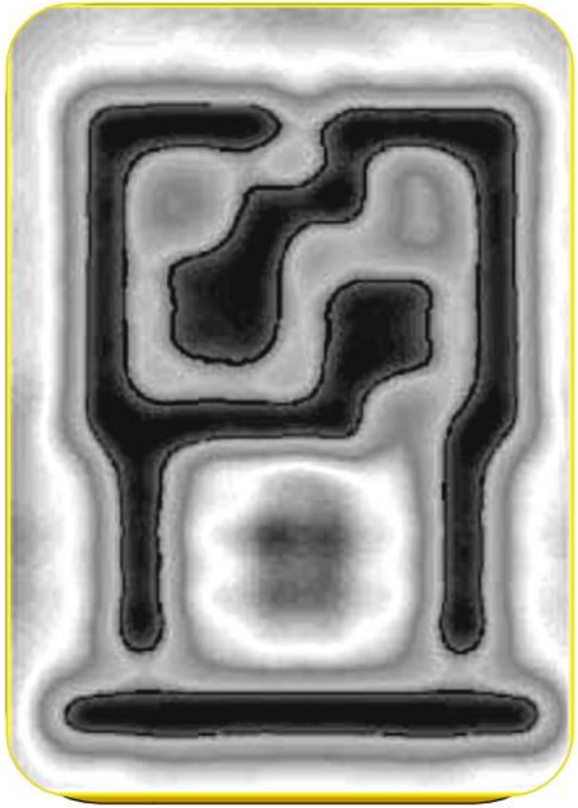
- Based on a physical system
- Easy to evaluate (using the physical system)
- Its output looks like a random function
- Unpredictable even for an attacker with physical access

Transistor

Sub-Wavelength

WYSINWYG

What You See Is Not What You Get

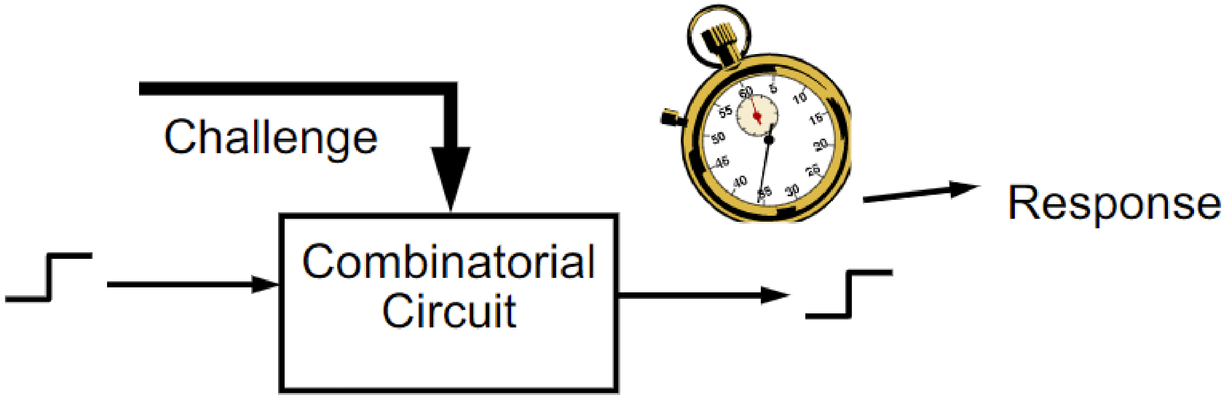


Process variations

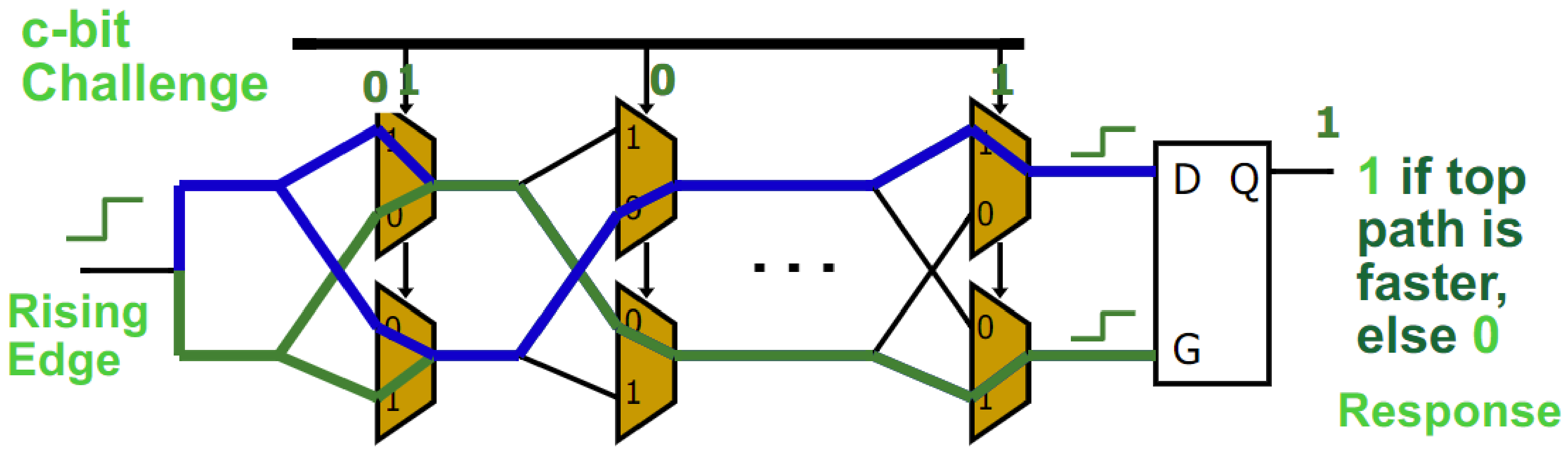
No two transistors have the same parameters

Silicon PUF

- 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.



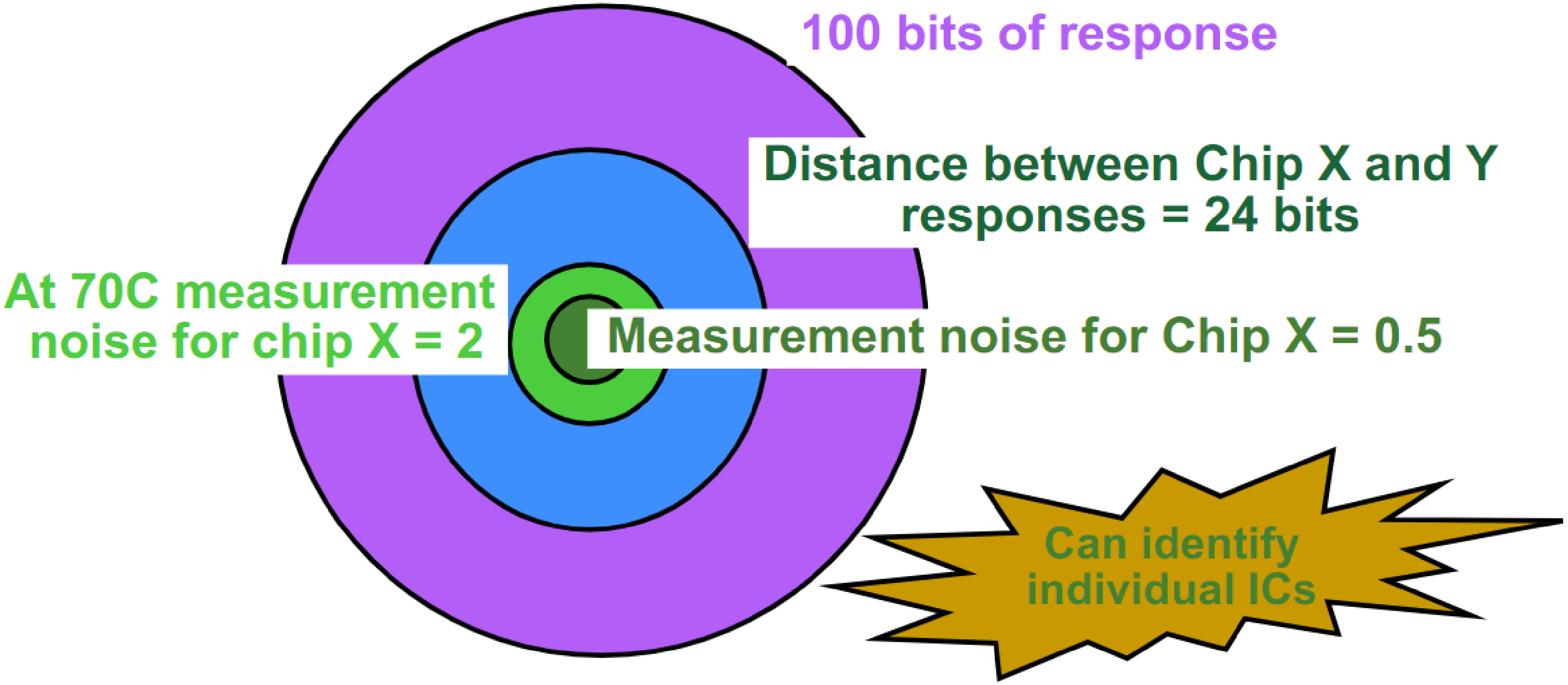
Silicon PUF Example



- 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**

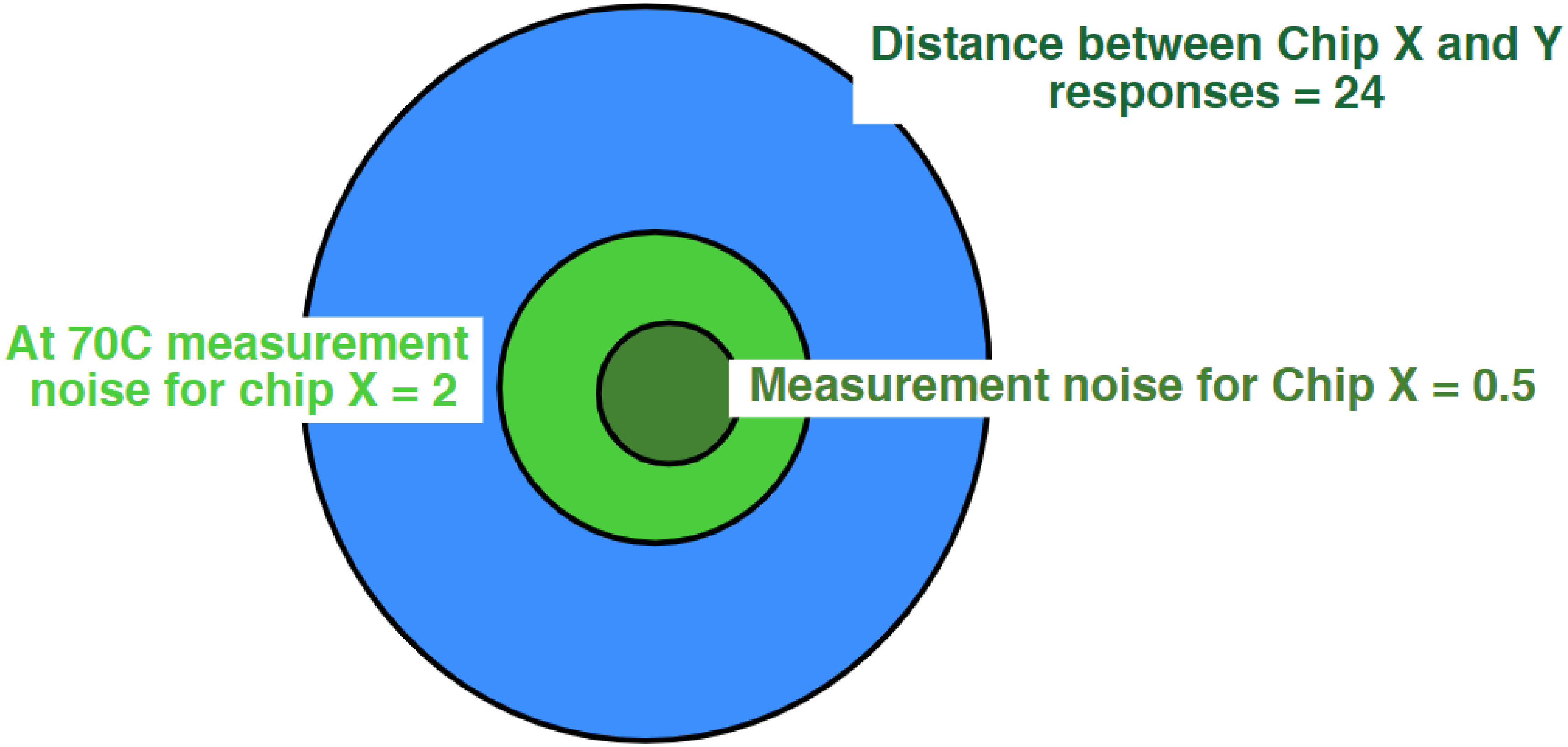
Experiments

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



Attacks

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



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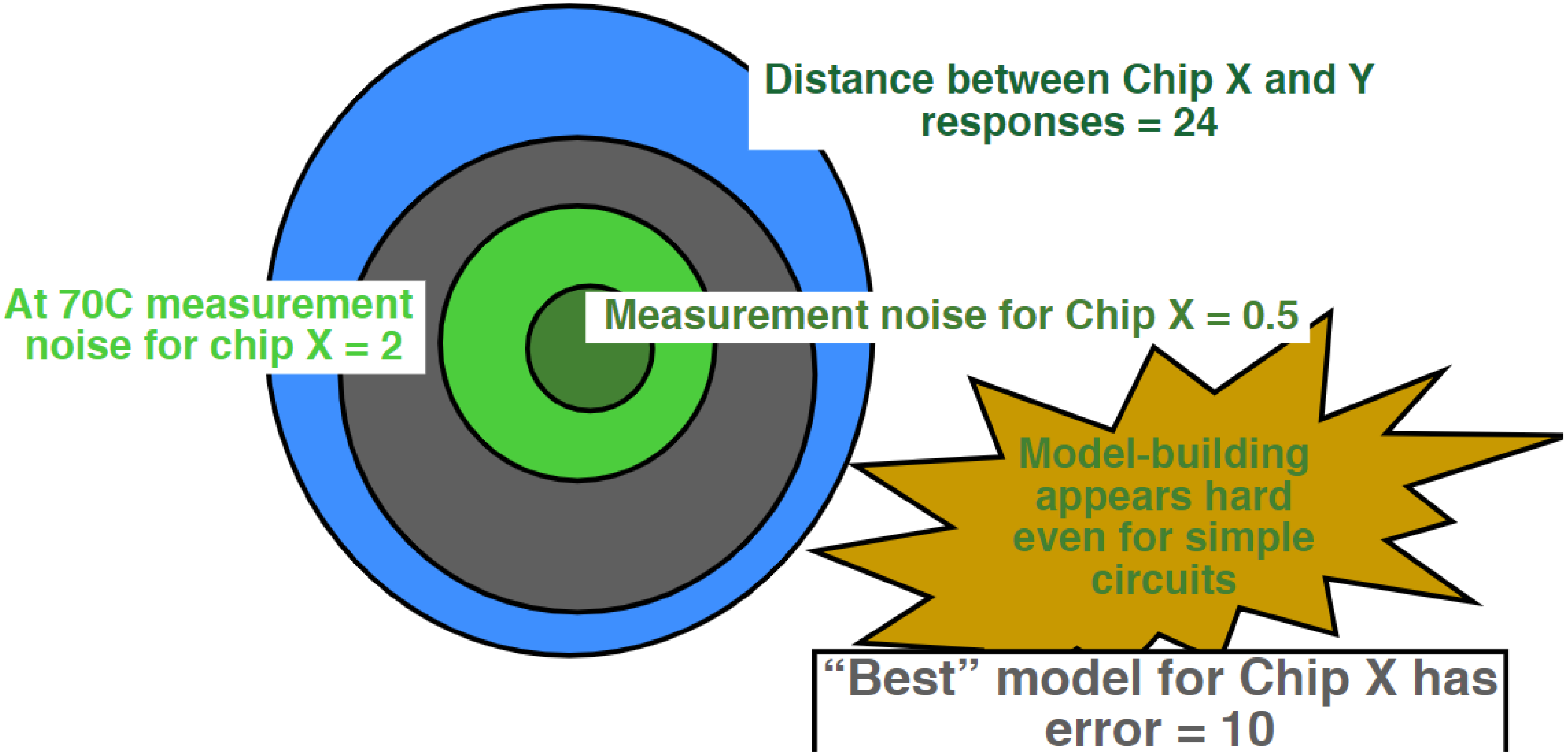


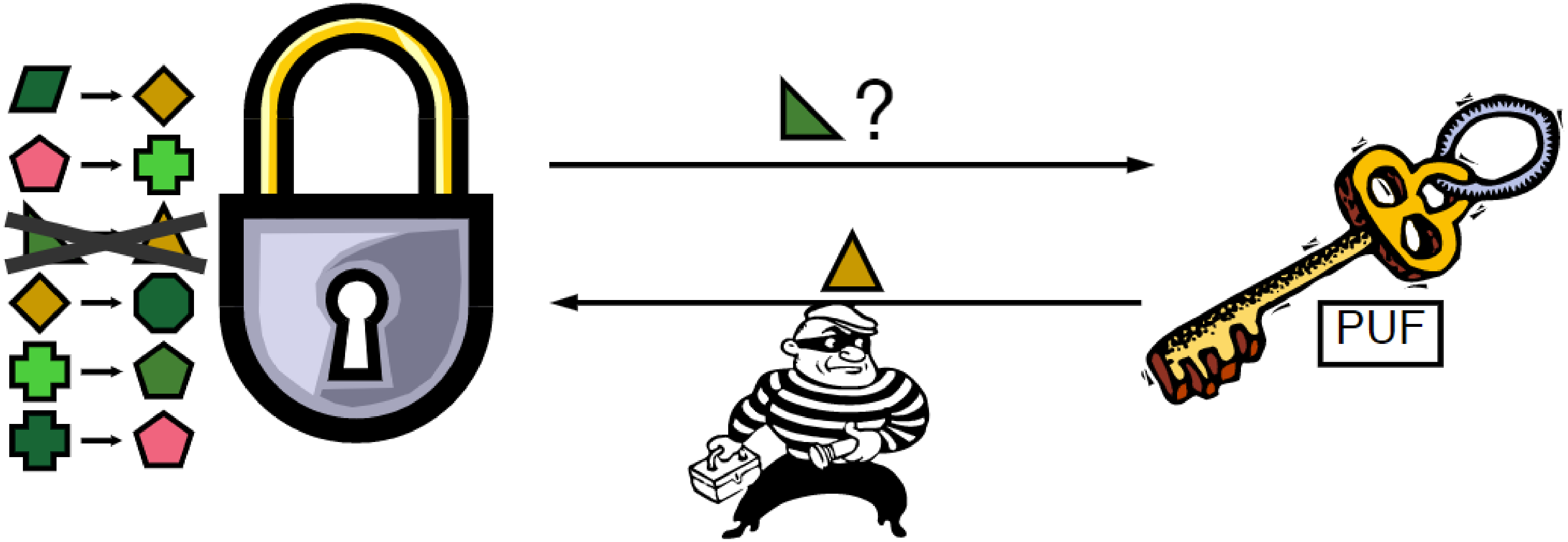
Physical Attacks

- 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

PUF as a 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.**



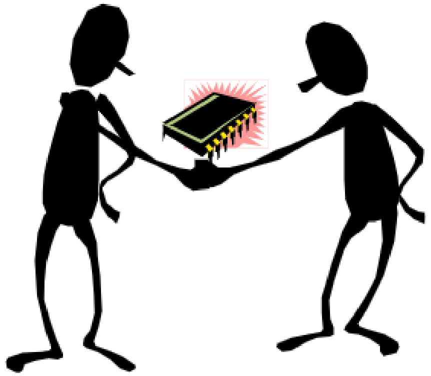
Applications

- **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.



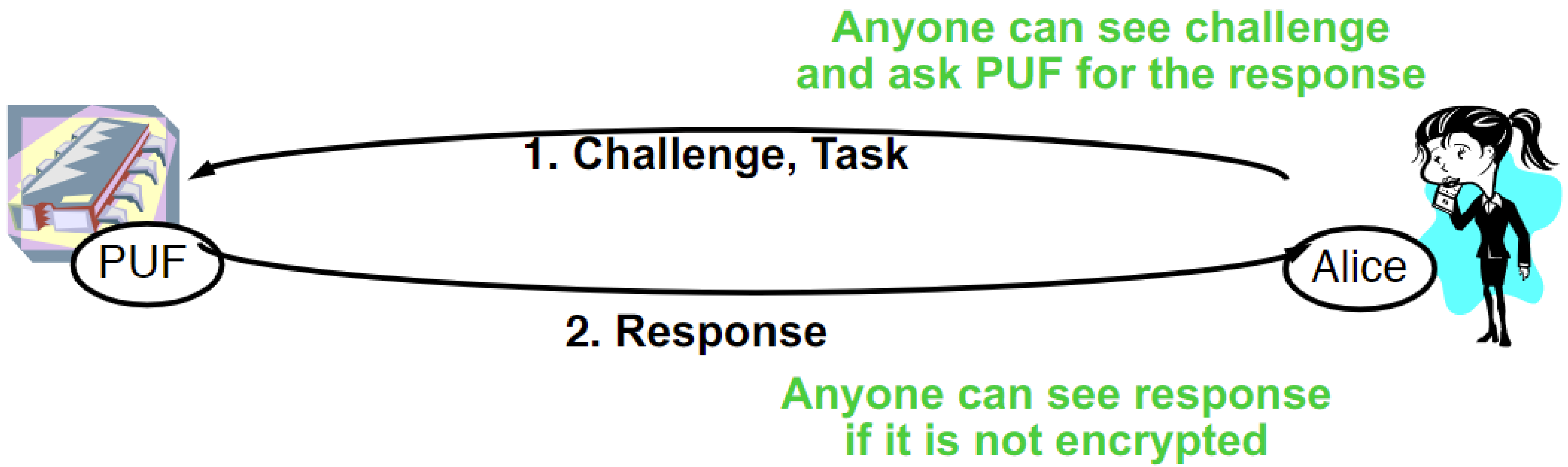
We can enable the above applications by trusting only a single-chip processor that contains a silicon PUF.

Applications

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

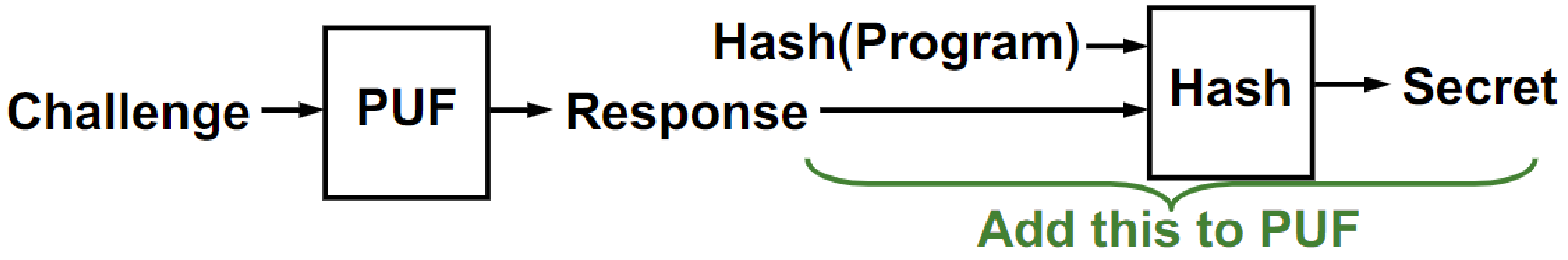


Access Restriction to PUF

- 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.

$\Rightarrow$ **Combine response with hash of program.**

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



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 $h(x) = h(y)$

Challenge-Response Pair

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

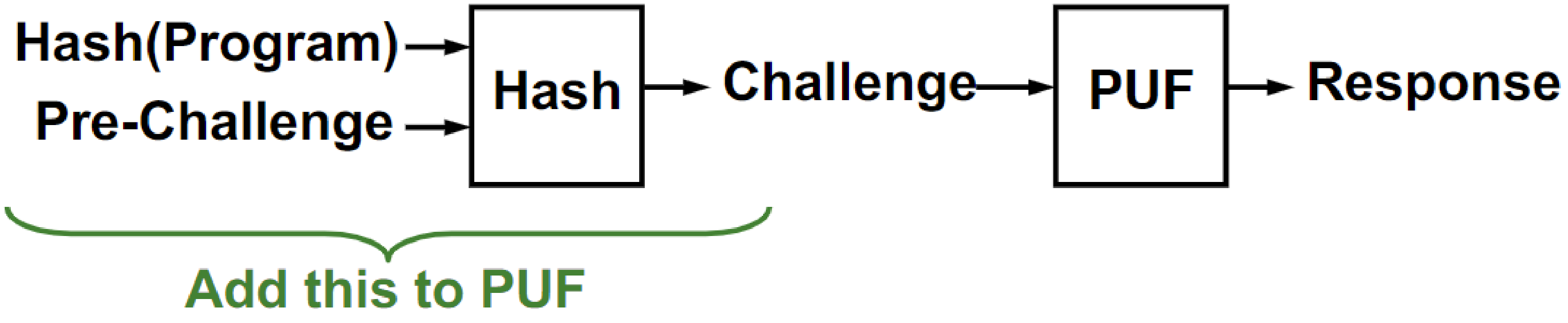
- But Alice can't get a Challenge-Response pair in the first place since the PUF never releases responses directly.

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

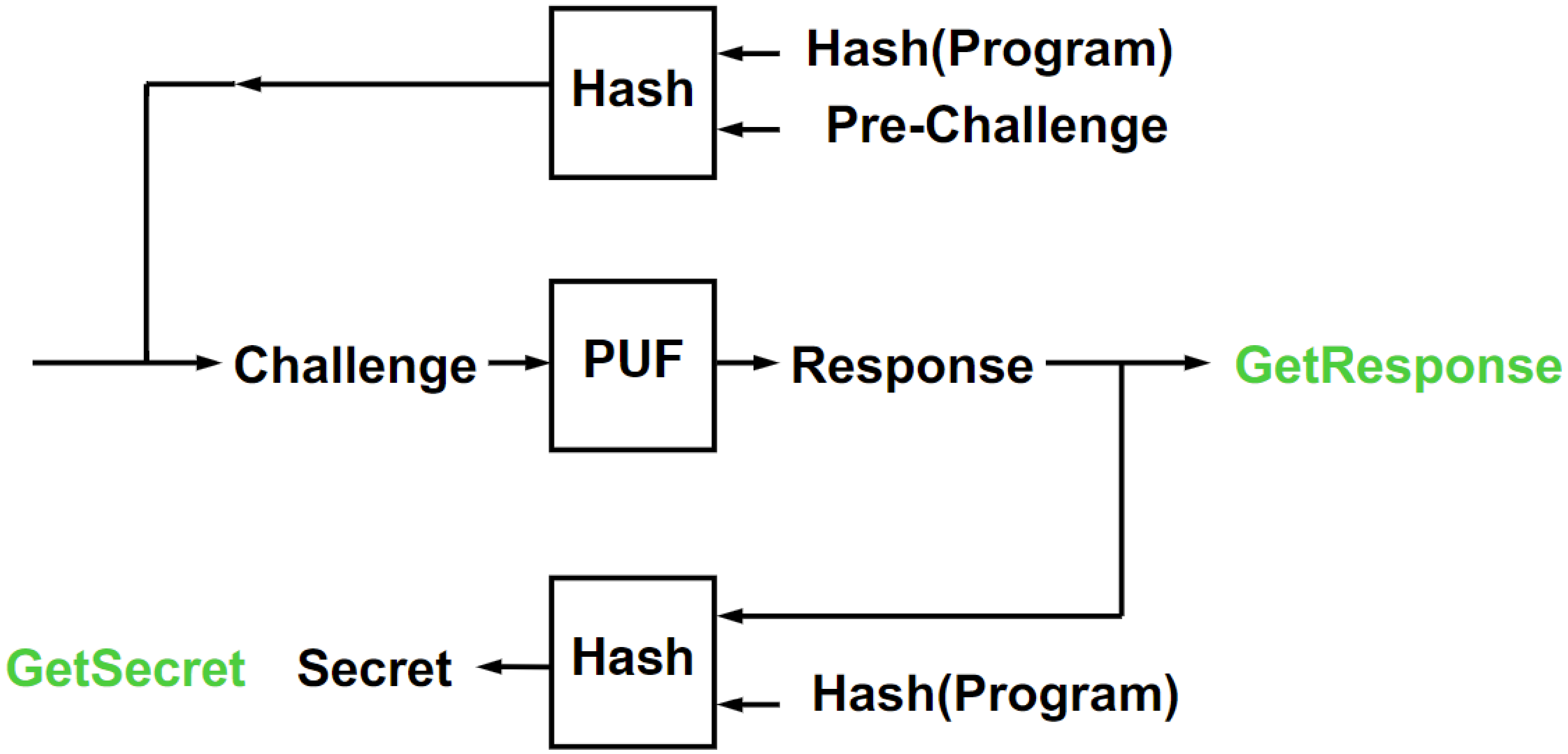
Challenge-Response Pair

- 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



C-R Pair Management

When a Controlled PUF (CPUF) has just been produced, the manufacturer wants to generate a challenge-response pair.

1. Manufacturer provides Pre-challenge and Program.
2. CPUF produces Response.
3. Manufacturer gets Challenge by computing Hash(Hash(Program), PreChallenge).
4. Manufacturer has (Challenge, Response) pair where Challenge, Program, and Hash(Program) are public, but Response is not known to anyone since Pre-challenge is thrown away