ECE 459/559
Secure & Trustworthy Computer Hardware Design

Physical Unclonable Functions
Basics

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General Security

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Authentication

What Do We Want to Achieve?

Authentication
no spoofing

Data Integrity
no data alteration

Privacy
no eavesdropping

Attacks

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

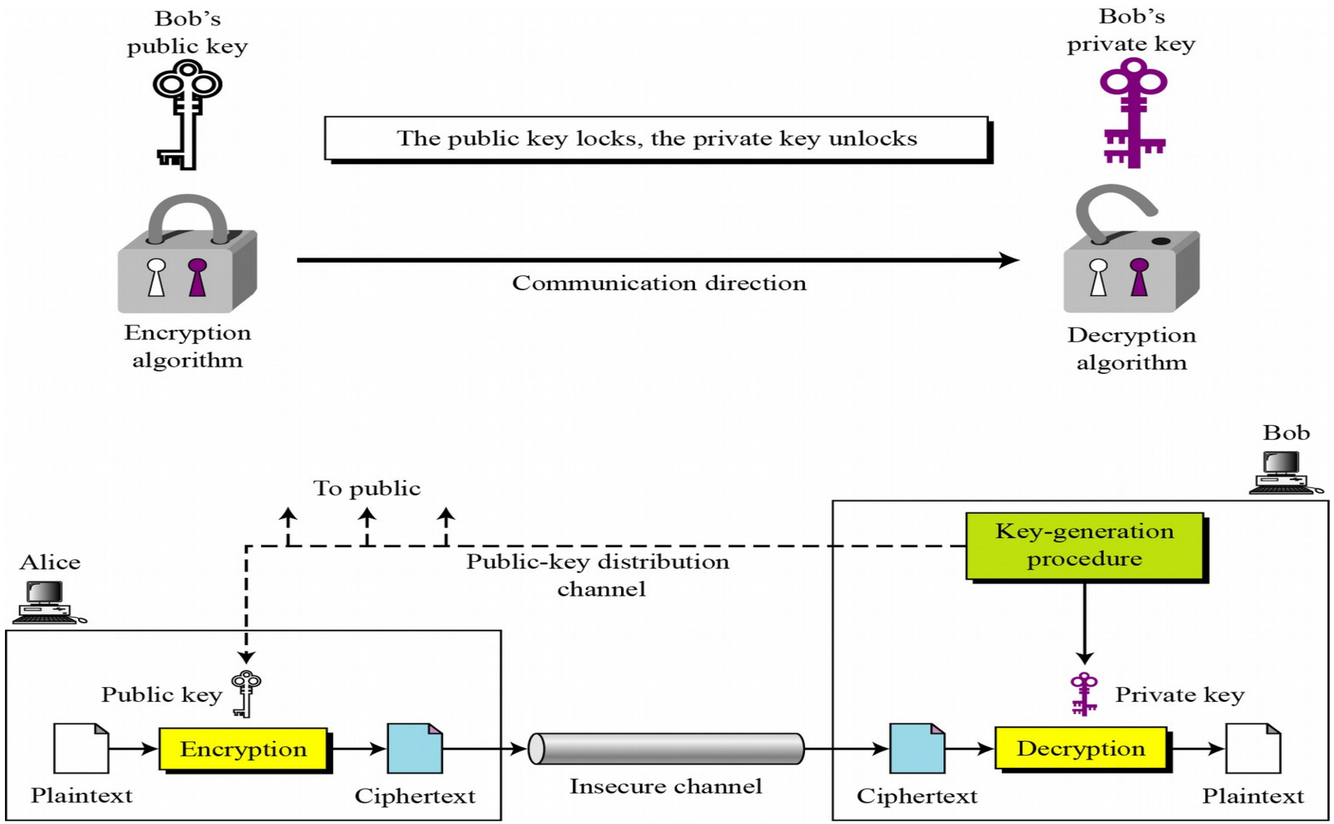
Threat Model – Attacker Goals

- Obtain crypto keys stored in RAM or ROM
- Learn the secret crypto algorithm used
- Obtain other information stored on-chip (e.g. PINs)
- Modify information on the card (e.g. calling card balance)

Some Terminology

- Keys are rules used in algorithms to convert a document into a secret document
- Two types of keys:
  - Symmetric
  - Asymmetric
- Symmetric if same key used for encryption and decryption
- Asymmetric if different keys for encryption and decryption

Asymmetric Security



Security of Asymmetric Keys

- Asymmetry between the information (secret)
- One-way functions
  - Easy to evaluate one direction, hard to reverse in other
  - E.g., multiplying large prime numbers as opposed to factoring
- One-way hash functions
  - Maps a variable length input to a fixed length output
  - Avalanche property: changing one bit in input alters nearly half the output bits
  - Preimage resistant, collision resistant
  - Usage: digital signature, secured password storage, file identification, and message authenticated code

Challenges of Algorithmic 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:
Physical One-Way Function

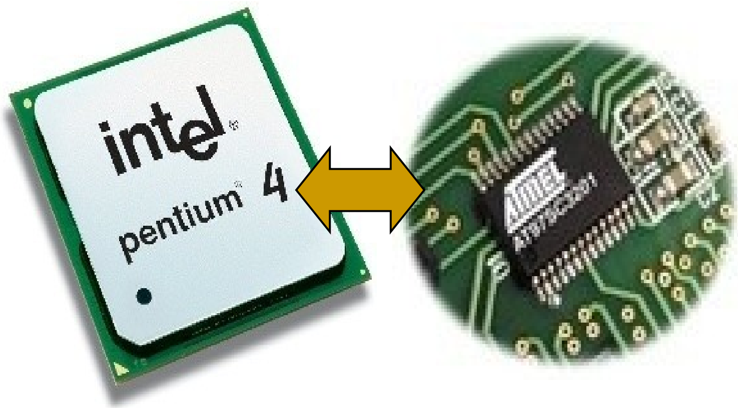
- Use the stochastic physical structures that are difficult to model instead of mathematical one-way functions
- Physical One-Way Function (POWF):
  - Inexpensive to fabricate
  - Prohibitively difficult to duplicate
  - No compact mathematical representation
  - Intrinsically tamper-resistant

Example: IBM 4758

- Goal: Store digital information such that physical attack is difficult and expensive
- IBM 4758
  - Cryptographic coprocessor with secret key generation and memory
  - Includes RNG
  - Tamper-proof package
  - Tens of sensors, resistance, temperature, voltage, etc.
  - Continually battery-powered
  - ~ $3,000 for a 99 MHz processor and 128 MB memory

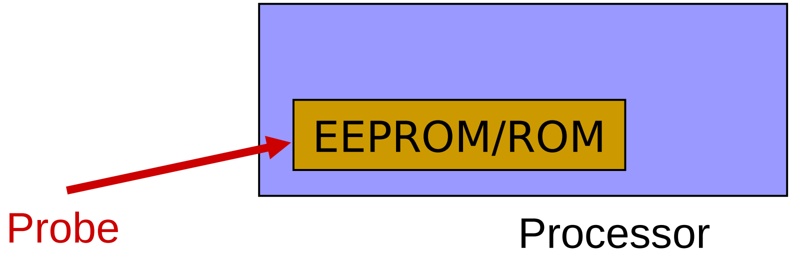
Trusted Platform Module (TPM)

- Separate chip (TPM) specifically designed for security functions
- TPM has become international standard for crypto processors
- Includes cryptographic key generation and RNG
- Decrypted “secondary” keys can be read out from bus



Problems…

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



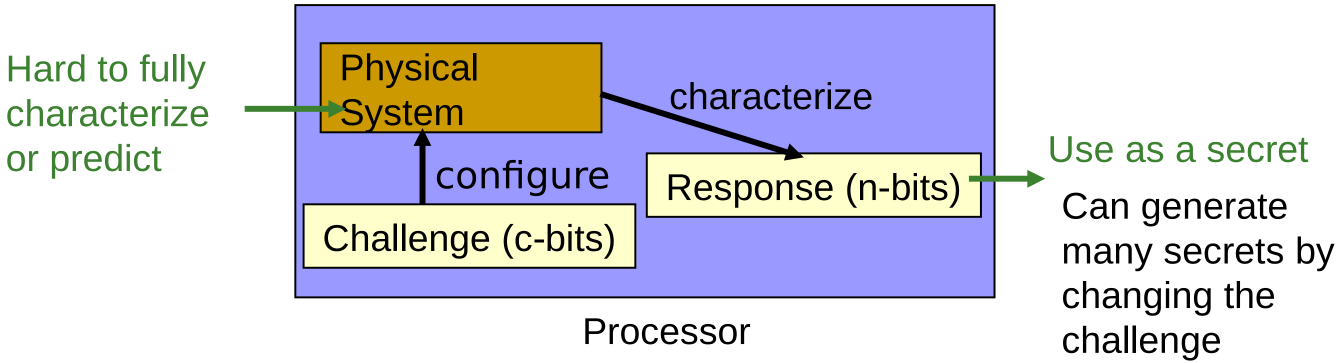
- Adversaries can physically extract secret keys from EEPROM while the processor is off
- Trusted party must embed and test secret keys in a secure location
- EEPROM adds additional complexity to manufacturing

Turn a Problem into Feature!

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

Physical Random Functions

- Generate keys from a complex physical system



- Security advantage:
  - Keys 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?

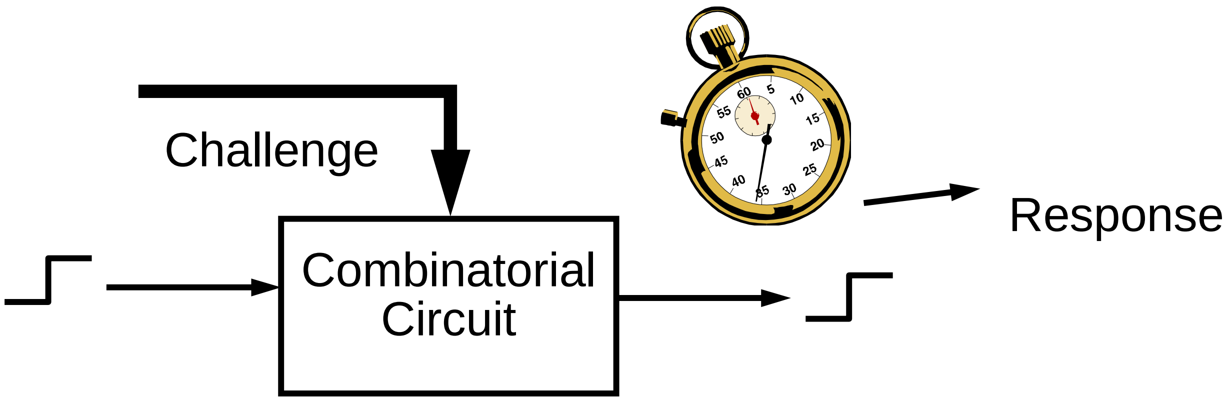
Gassend, et al., “Silicon Physical Random Functions,” CCS 2002.

The PUF Defined

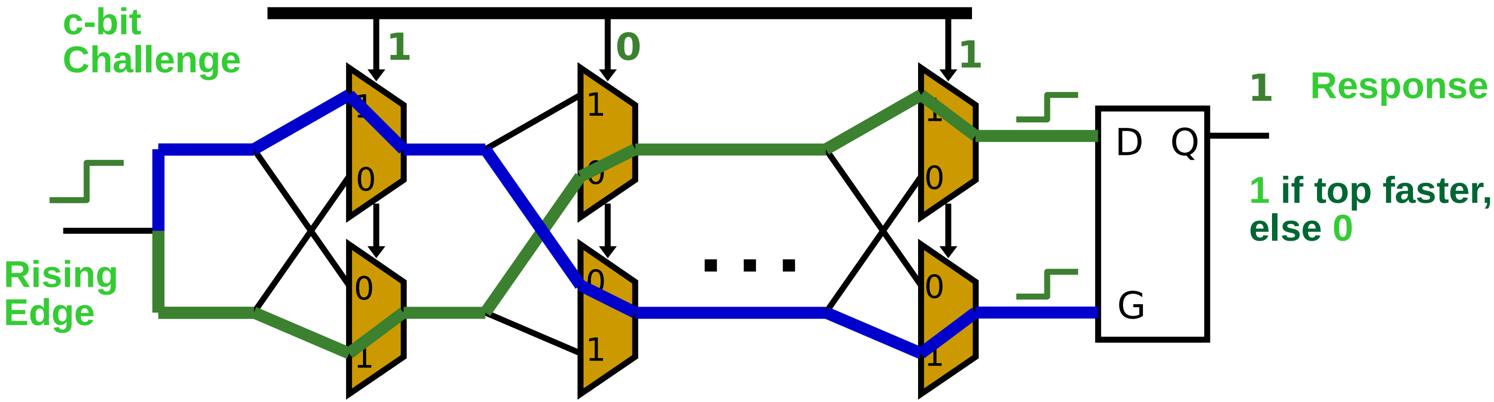
- Physical Random Function or Physical Unclonable Function (PUF) is a function that is:
  - Based on a physical system
  - Easy to evaluate *using the physical system*
  - Output looks like a random/unclonable function
  - Unpredictable even for attacker with physical access

Electronic Silicon PUF

- Due to process variations, no two integrated circuits are identical
- Experiments in which identical circuits with identical layouts are placed on different ICs/FPGAs show that path delays vary enough across ICs to use for identification



The Arbiter PUF



- Compare two paths designed for identical delay
  - Random process variations determine which path faster
  - Arbiter output is 1-bit, representing fastest path
- Path delays in an IC are statistically distributed due to random manufacturing variations

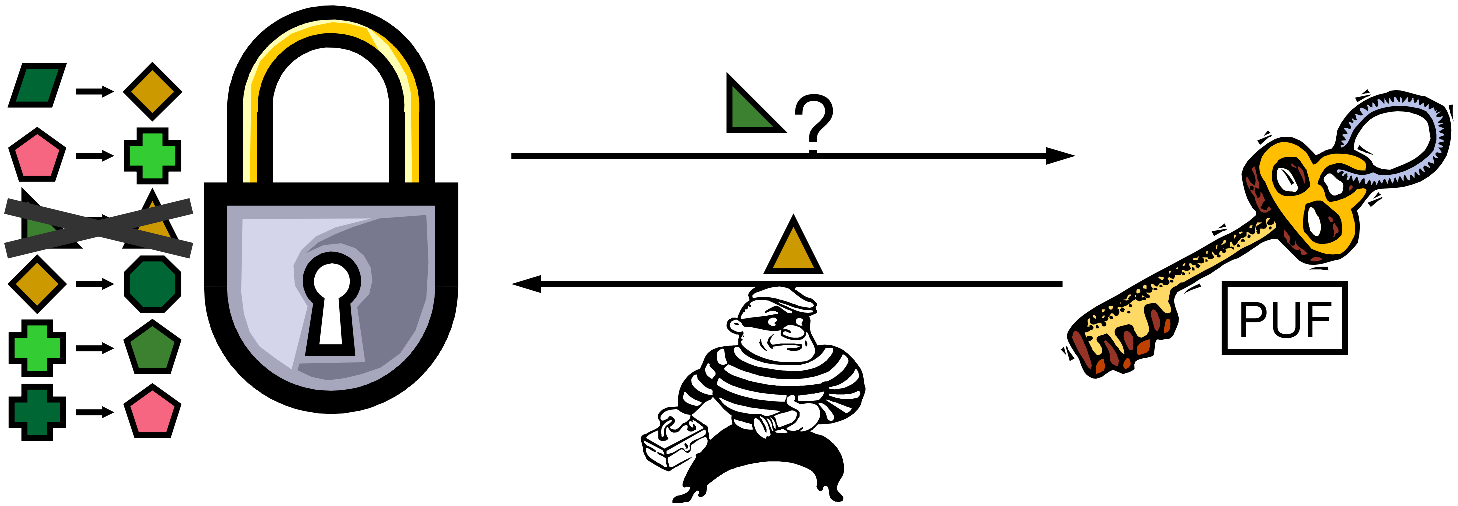
Suh et al., “Physical Unclonable Functions,” DAC 2007.

Physical Attacks

- PUF delays should depend only on physical variations
  - Must minimize any “bias by design”
    (e.g. wire length, transistor sizing, symmetry)
- Invasive attack (e.g., package removal) changes PUF delays and destroys PUF
- Non-invasive attacks are still possible
  - To find wire delays we need precise relative timing of transient signals as opposed to looking for 0's and 1's
  - Wire delay not a number but function of challenge bits and adjacent wire voltages

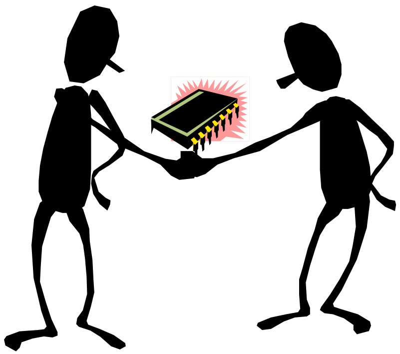
PUF as Unclonable Key

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



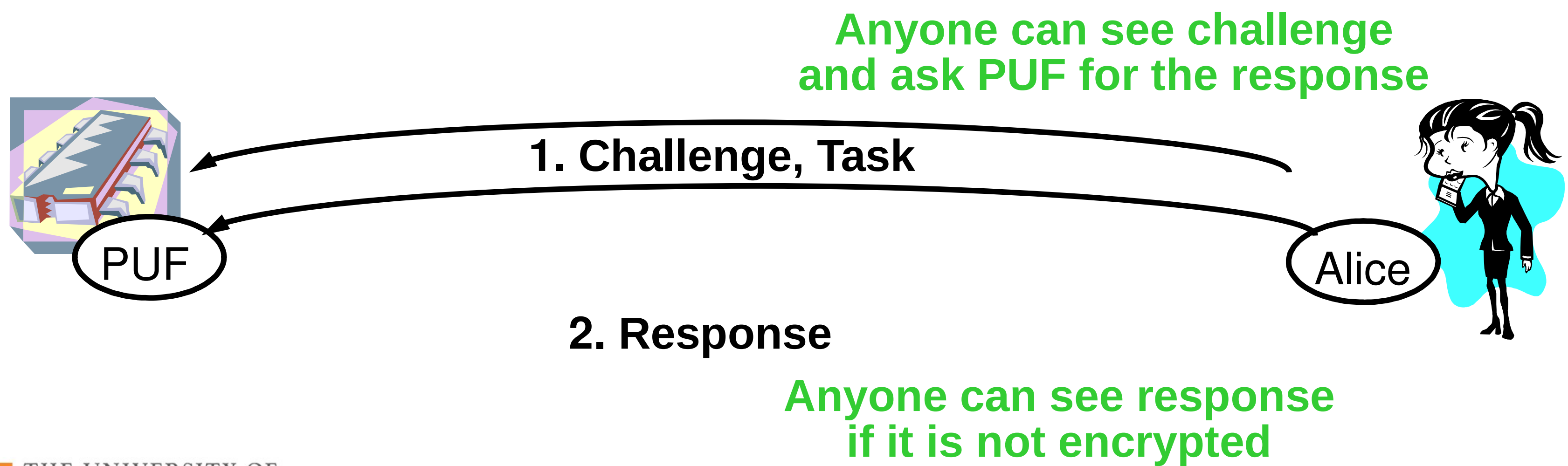
Applications

- Anonymous Computation
  - Alice wants to run computations on Bob's computer & wants to make sure she is getting correct results
  - Certificate returned with her results to show 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)
  - Program is copy-protected so it will not run on any other chip
- Can enable above applications by trusting only single-chip processor that contains a PUF



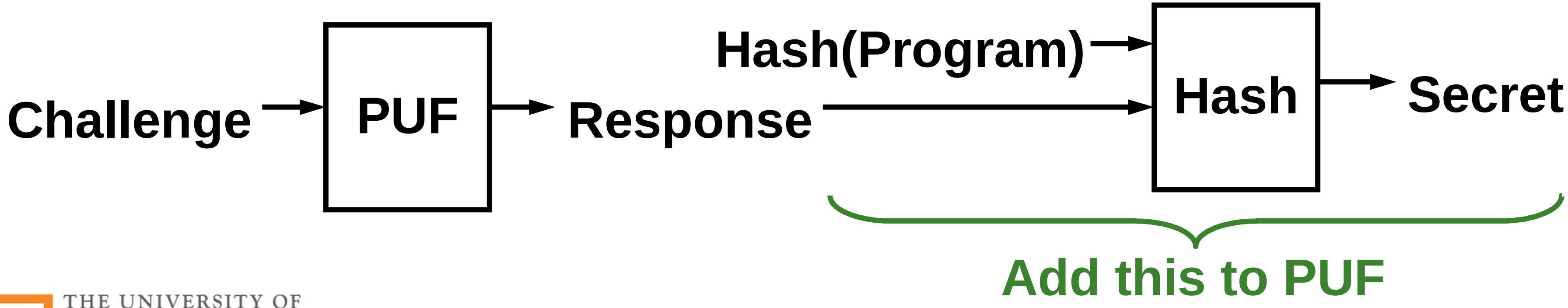
Sharing Secrets using a PUF

- Suppose Alice wishes to share secret using a 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 PUF Access

- To prevent attack, man in the middle must be prevented from finding the response
- Alice's program can establish a shared secret with the PUF, attacker's program must not be able to get secret
  - Combine PUF response with hash of program
- PUF can only be accessed via the GetSecret function:



Gassend et al., “Controlled Physical Random Functions,” ACSAC 2002.

Cryptographic Hash Function

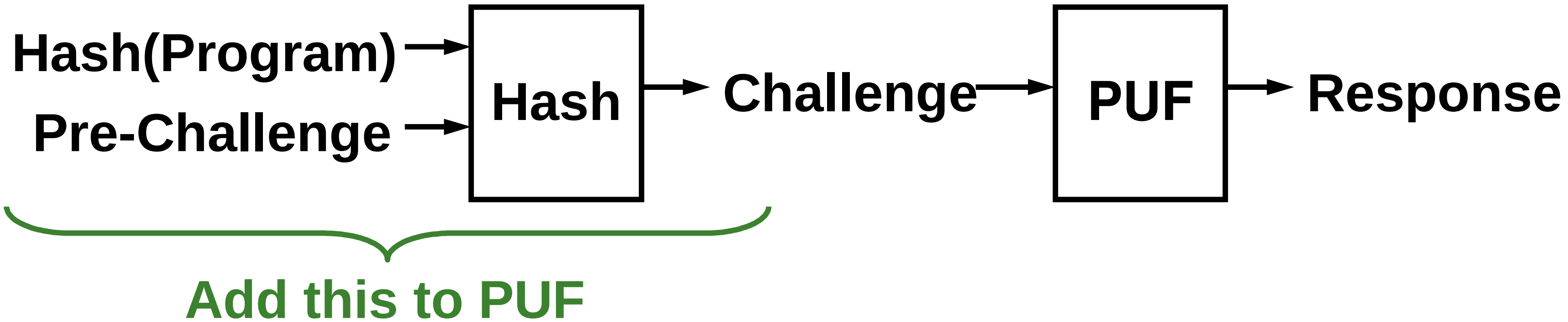
- Crypto hash function h(x) must provide:
  - Compression – output length is small
  - Efficiency – h(x) easy to compute for any x
  - One-way – given value y it is infeasible to find an x such that h(x) = y
  - Weak collision resistance – given x and h(x), infeasible to find y ≠ x such that h(x) = h(y)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

Getting a Challenge-Response Pair

- Now Alice can use a Challenge-Response pair to generate shared secret with PUF equipped device
- But Alice can't get a Challenge-Response pair in the first place since the PUF does not directly release responses
  - Only releasing “Secret” or hash of program + response
  - Extra function that can return responses needed

Getting a Challenge-Response Pair

- Let Alice use a Pre-Challenge
- Use program hash to prevent eavesdroppers from using the pre-challenge
- PUF has GetResponse Function



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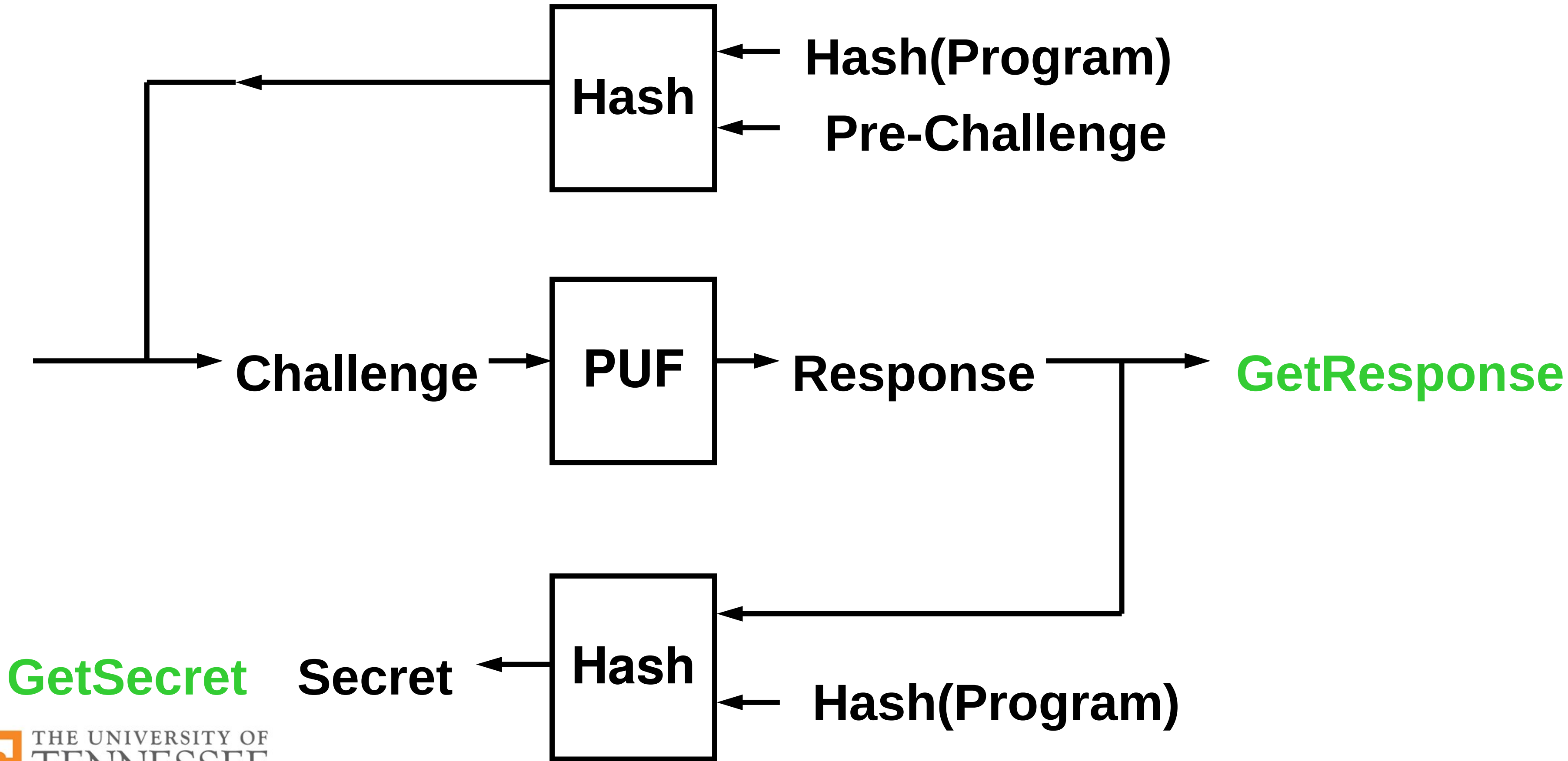
Controlled PUF Implementation



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Gassend et al., “Controlled Physical Random Functions,” ACSAC 2002.

Challenge-Response Pair Management: Bootstrapping

- When controlled PUF (CPUF) has just been produced, manufacturer wants to generate challenge-response pair
  - Manufacturer provided PreChallenge & Program
  - CPUF produces Reponse
  - Manufacturer gets Challenge by computing Hash(Hash(Program), PreChallenge)
  - Manufacturer has (Challenge, Response) pair where Challenge, Program, and Hash(Program) are public but Response not known since PreChallenge thrown away

Gassend et al., "Controlled Physical Random Functions," ACSAC 2002.

Summary

- PUFs provide secret “key” and CPUFs enable sharing a secret with a hardware device
- CPUFs are not susceptible to model-building attack if we assume physical attacks cannot discover PUF response
  - Control protects PUF by obfuscating response, PUF protects control by “covering up” control logic
  - Shared secrets are volatile