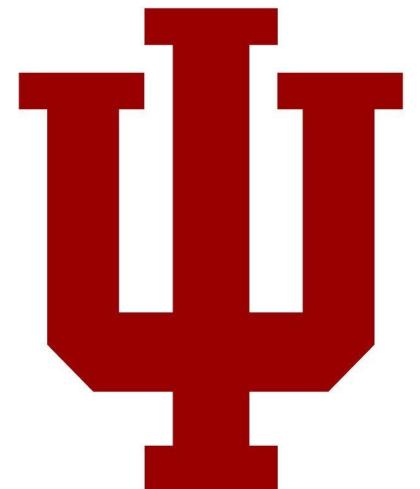


# Introduction to Hardware Security

Engr 399/599: Hardware Security

Grant Skipper

*Indiana University*



Adapted from: Mark Tehranipoor of University of Florida

Course Website

enr599.github.io

Write that down!

# Why Hardware Security?

*Cybersecurity experts have traditionally assumed that the hardware underlying information systems is secure and trusted.*

***Such assumptions are not true.***

# The goals of this class are to:

- Learn the state-of-the-art security primitives and methods
- Integration of security as a design metric
- Protection of the design intellectual property against piracy and tampering
- Understanding of attacks and countermeasures
- Understanding of vulnerabilities in design and fabrication processes

# Course Topics

- Hardware Security and Trust
- Hardware Cryptography
- Physically-Unclonable Functions (PUFs)
- True Random Number Generation (TRNG)
- Hardware Metering and Watermarking
- Hardware Physical and Fault-Injection Attacks
- Hardware Trojans
- Counterfeit Detection
- Side Channel Analysis
- FGPA Security
- PCB Security

# About Me - Professor

**Grant Skipper**, Microelectronic Security Engineer  
Office Hours: Monday, TBD

Main research work is on security for FPGA-based systems, hardware Trojans, and reverse engineering embedded devices

Ph.D. in Intelligent Systems Engineering from IU - 2022



# About Chris - TA

**Chris Sozio**, Ph.D. student in Intelligent Systems Engineering

Office Hours: TBD

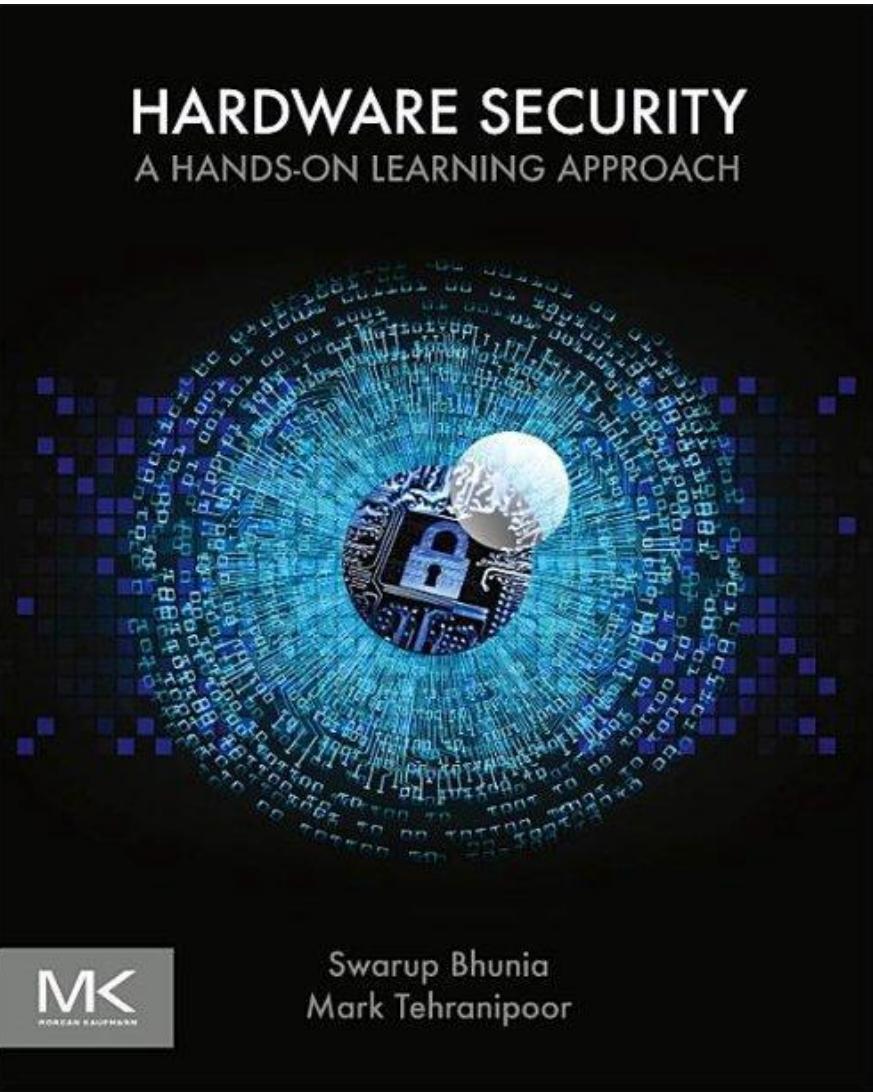
Main research work is on security for FPGA-based systems, and hardware Trojans

B.S. in Computer Science from IU - 2019



# About You?

- Name
- Year / Department
- Why did you take this class?
- What are you hoping to learn?
- What's your background? Cybersecurity? Hardware?



- Available online through IU's Library (See syllabus)

# Grading

- The syllabus currently says this:

Exams	Projects	Participation
25%	40%	10%

- **This might change.** We're still working out the projects.
- Attendance is part of participation this semester.

# A note on the slides

- These slides are adapted from an equivalent course at the University of Florida
- They can be dense
- Please stop me and ask questions

# More to Read ...

---

- **Reading**
  - Papers from the contemporary literature
- **Further possible reading**
  - Mihir Bellare and Phil Rogaway, **Introduction to Modern Cryptography**
  - Ross J. Anderson. **Security Engineering: A guide to building dependable distributed systems**. John Wiley and Sons, 2001
  - Matt Bishop, **Computer Security: Art and Science**, Addison-Wesley, 2003
  - William Stallings. **Cryptography and Network Security**, Fourth edition, 2007
  - M. Tehranipoor and F. Koushanfar, "**A Survey of Hardware Trojan Taxonomy and Detection**," IEEE Design and Test of Computers, 2010.
  - M. Tehranipoor, H. Salmani, and X. Zhang, **Integrated Circuit Authentication: Hardware Trojans and Counterfeit Detection**, Springer July 2013.
  - U. Guin, D. DiMase, and M. Tehranipoor, "**Counterfeit Integrated Circuits: Detection, Avoidance, and the Challenges Ahead**," Journal of Electronic Testing: Theory and Applications (JETTA), Feb. 2014.

# More to Watch!

---

## ■ Videos

- What's inside a microchip? <http://www.youtube.com/watch?v=GdqbLmdKgw4>
- Zoom Into a Microchip <http://www.youtube.com/watch?v=Fxv3JoS1uY8>
- Public Key Cryptography: RSA Encryption:  
[http://www.youtube.com/watch?v=wXB-V\\_Keiu8](http://www.youtube.com/watch?v=wXB-V_Keiu8)
- Counterfeit Electronics Could Be Dangerous, Funding Nefarious People  
<http://www.youtube.com/watch?v=dbZiUe6quxc>
- How Computers and Electronics Are Recycled  
<http://www.youtube.com/watch?v=lw4g6H7alvo>
- Counterfeit Electronic Components Process  
[http://www.youtube.com/watch?v=5vN\\_7NJ4qYA](http://www.youtube.com/watch?v=5vN_7NJ4qYA)
- Counterfeit Inspection <http://www.youtube.com/watch?v=MbQUvu2LN6o>
- Gold from waste circuit electronics <http://www.youtube.com/watch?v=ZkhOuNvkuu8>
- Tarnovsky Deconstruct Processor  
<https://www.youtube.com/watch?v=w7PT0nrK2BE>
- Creating iphone from scratch using black market parts!  
<https://www.youtube.com/watch?v=leFuF-zoVzA>

# Software Tools Needed for Projects and HWs

---

- PC or Mac or Linux Platforms are OK.
  - Python
  - Rust, probably
- Verilog/VHDL Tools:
  - Synopsys / Xilinx design flow
- Projects Involving FPGA Development Board
  - Xilinx Vivado Synthesis tools (student edition would suffice)

# Cyber Security Iceberg

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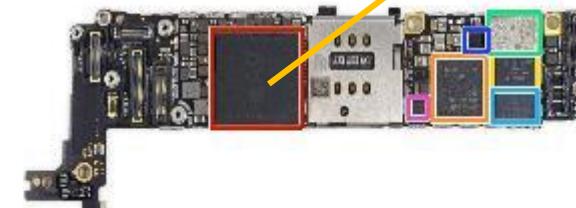
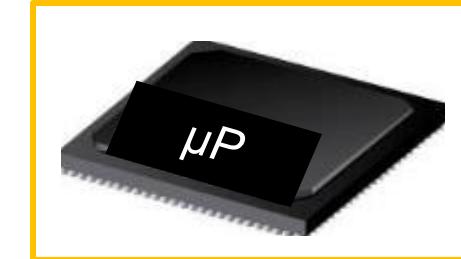
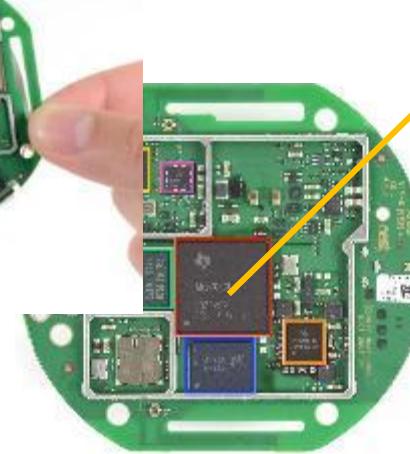
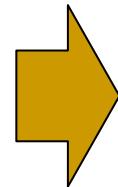
- 3 Domains of Cybersecurity (What's the difference??)
- CIA Triad

# Cyber Security Iceberg

---

- 3 Domains of Cybersecurity (What's the difference??)
  - Software/Application Security
  - Embedded/Firmware Security
  - Hardware/ASIC Security
- CIA Triad
  - Confidentiality: Information is protected.
  - Integrity: Information is accurate and not modified.
  - Availability: Information can be accessed when needed.

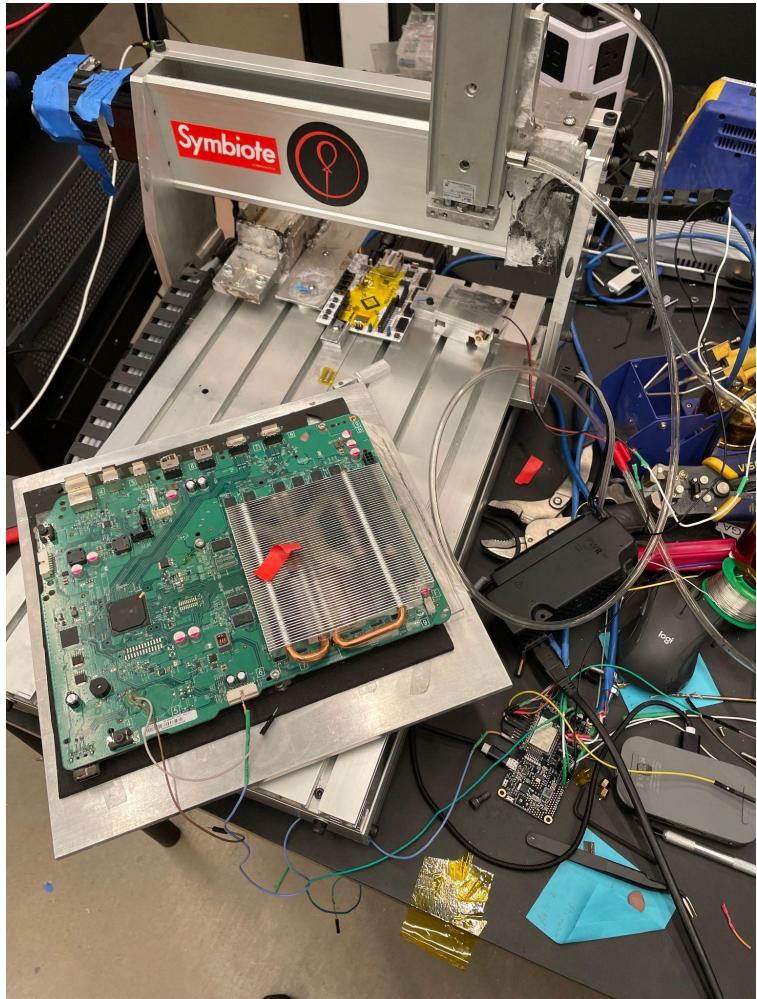
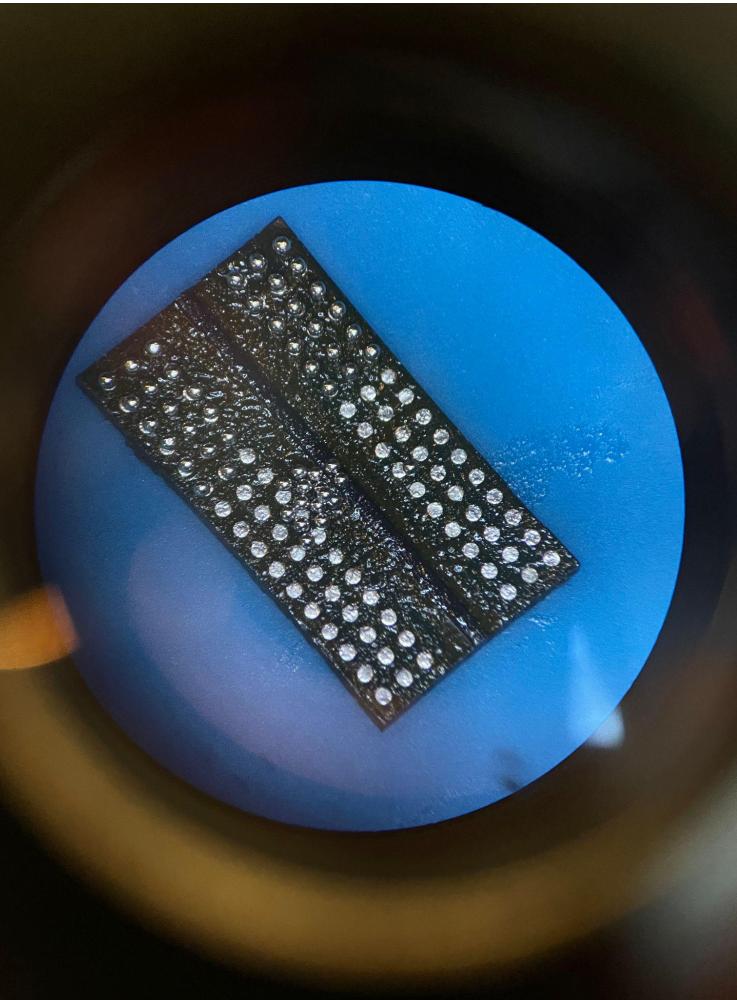
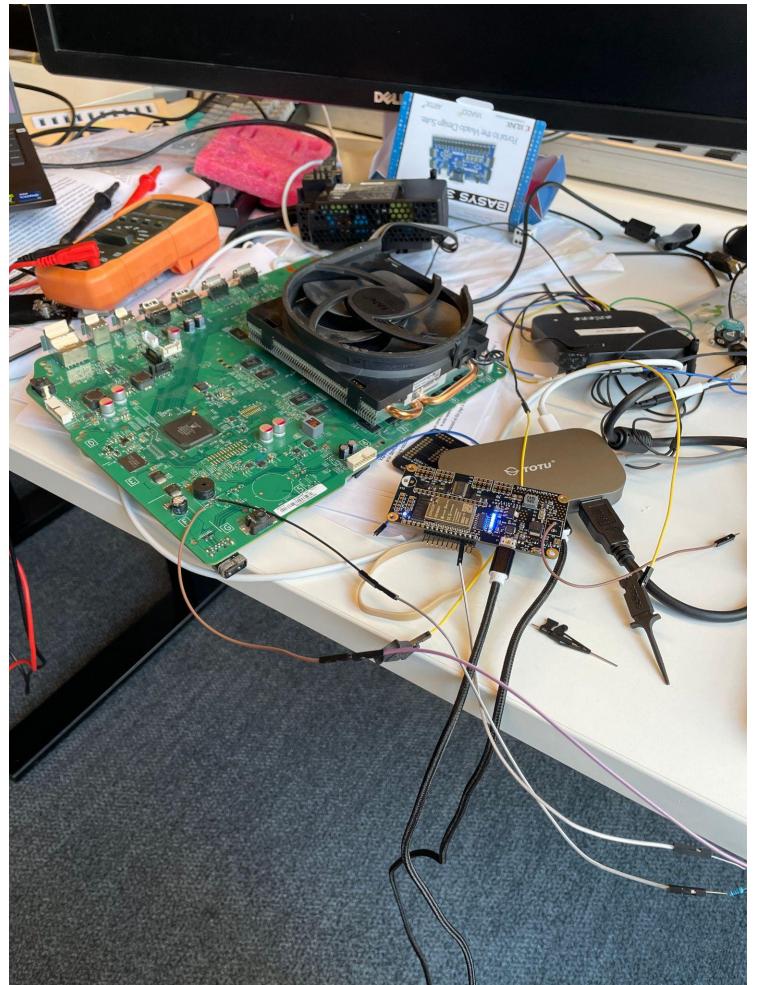
# What is Hardware?



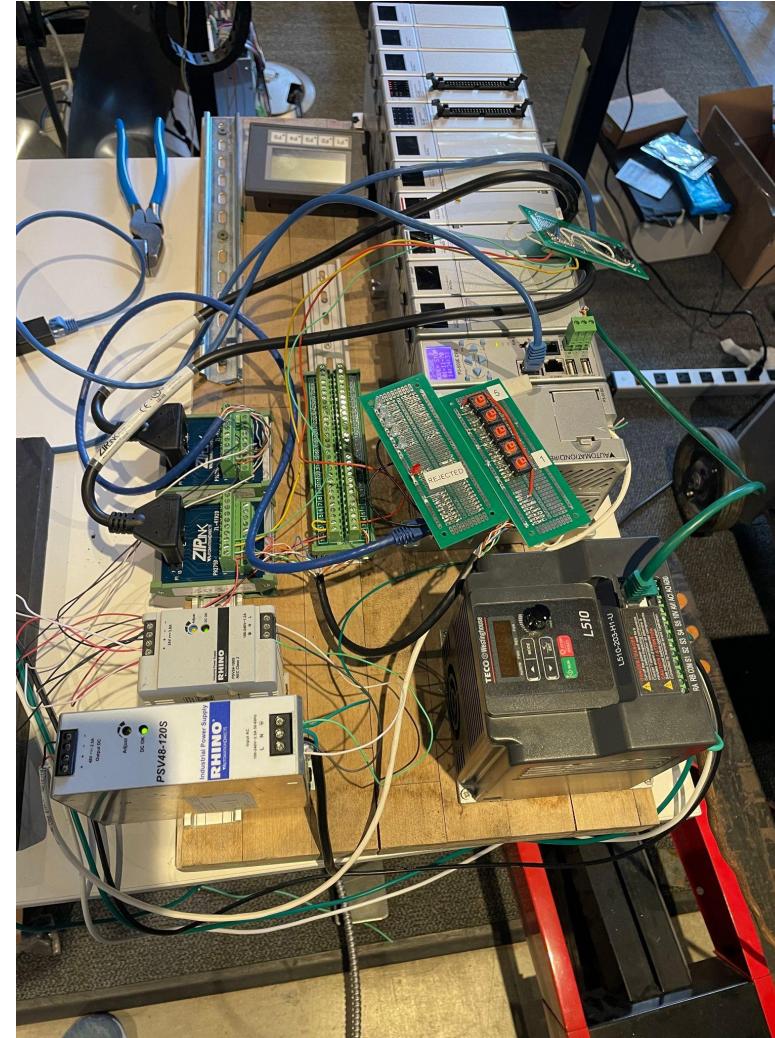
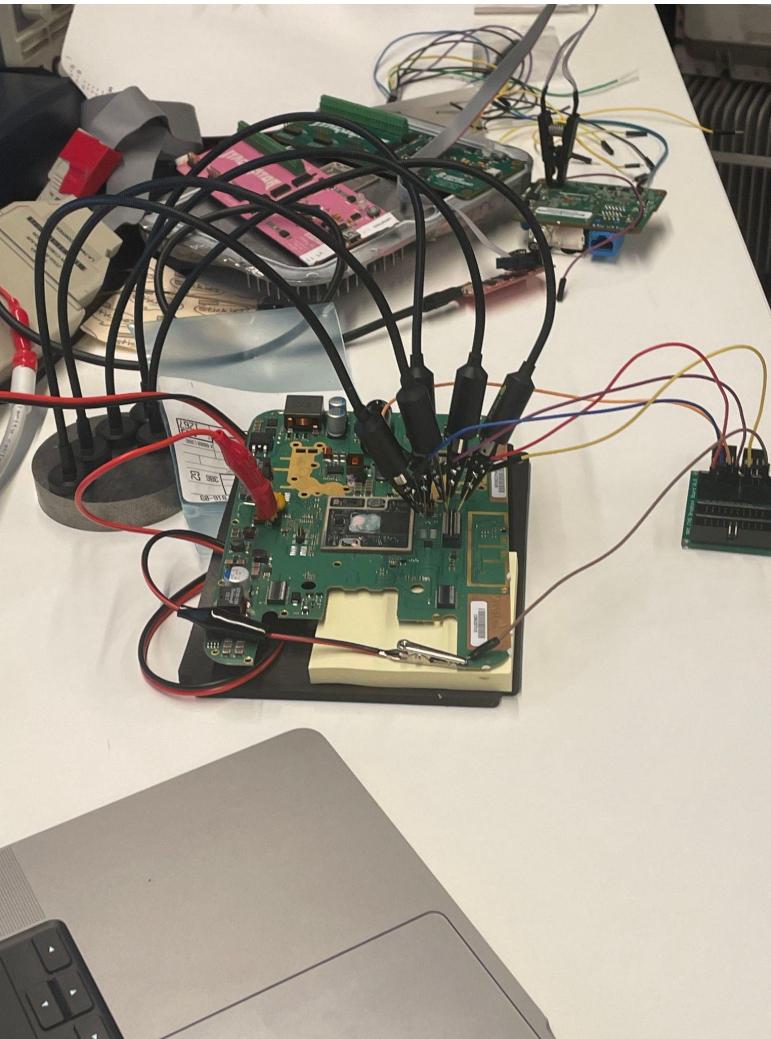
- Electronic System
- System Hardware – acts as the “*root-of-trust*”: PCB → IC (SoC |  $\mu$ P)

# What is Hardware?

---

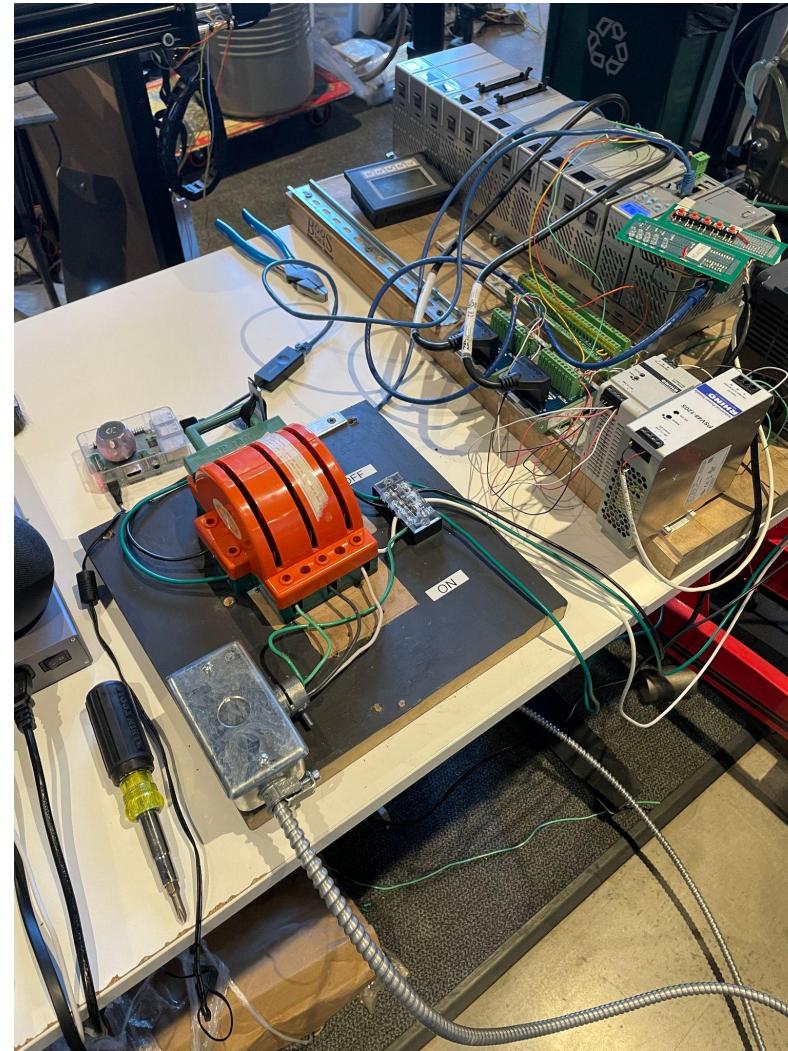
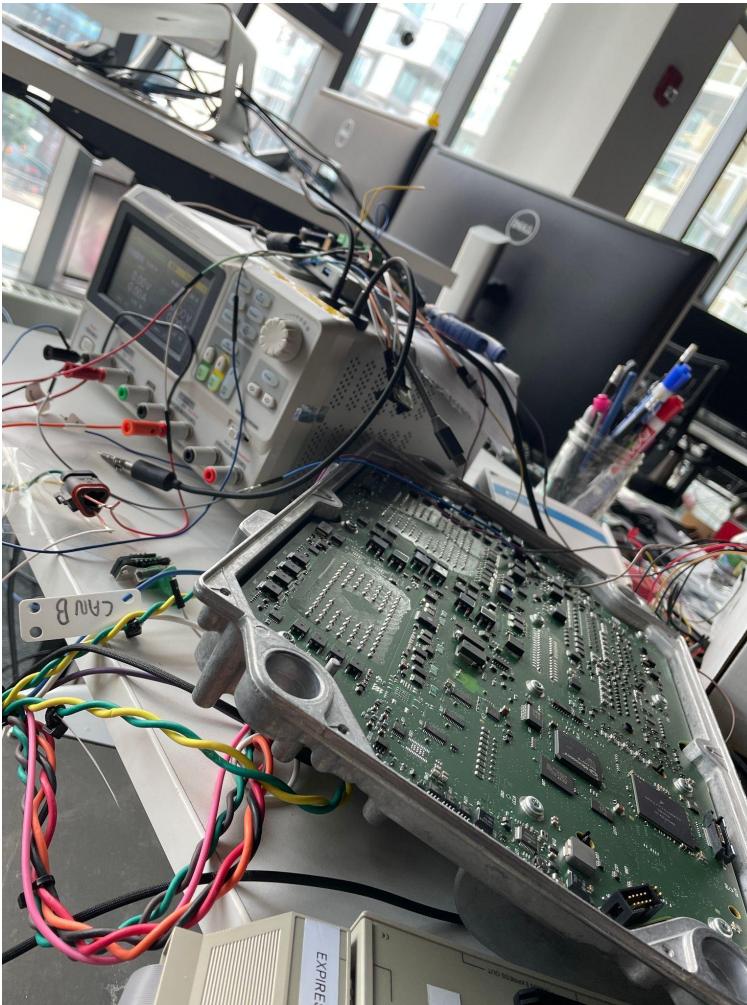


# What is Hardware?



# What is Hardware?

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# What is a “Root-of-Trust”?

- What is a “Chain of Trust”?
- Fun Slides on hacking RoT

# What is a “Root-of-Trust”?

- What is a “Chain of Trust”?
- Fun Slides on hacking RoT

Foundational Security Components that all higher abstraction security components build upon.

# Example Attack

---

Roy Zoppoth stands over a Xerox 914 copy machine, the world's first, which was used in soviet embassies all over the world. The machine was so complex that the CIA used a tiny camera designed by Zoppoth to capture documents copied on the machine by the soviets and retrieved them using a "Xerox repairman" right under the eyes of soviet security.

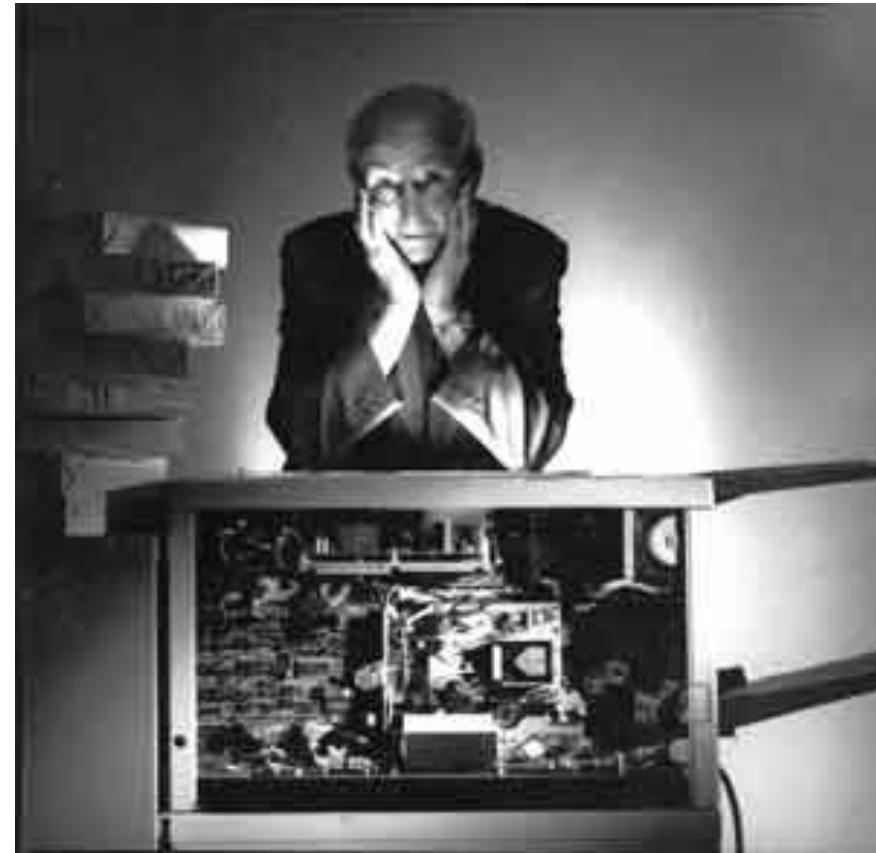


Photo from edit international courtesy of Roy Zoppoth

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# Motivation – HW Security



- **HW security is becoming increasingly important**
  - Hardware security sneaks into PCs, Robert Lemos, CNET News.com, 3/16/05
  - Microsoft reveals hardware security plans, concerns remain, Robert Lemos, SecurityFocus 04/26/05
  - Princeton Professor Finds No Hardware Security In E-Voting Machine, Antone Gonsalves, InformationWeek 02/16/07
  - Secure Chips for Gadgets Set to Soar, John P. Mello Jr. TechNewsWorld, 05/16/07
  - Army requires security hardware for all PCs, Cheryl Gerber, FCW.com, 7/31/2006

# Example Attack

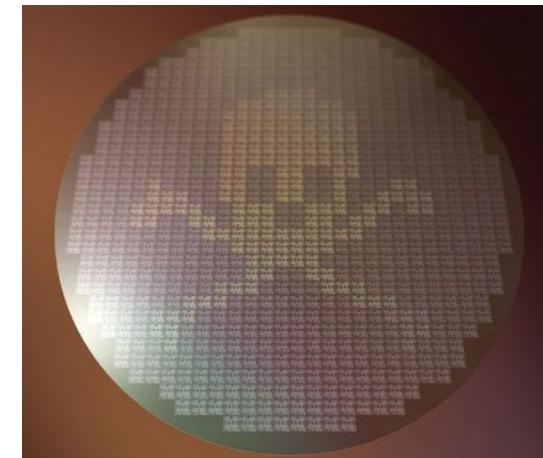
## DHS: Imported Consumer Tech Contains Hidden Hacker Attack Tools

- Top homeland securities have admitted instances where along with software, hardware components that are being imported from foreign parties and used in different US systems are being compromised and altered to enable easier cyber-attacks.
- **NEW**  
<https://www.nytimes.com/2019/11/07/nyregion/aventura-china-cameras.html>



## The Hunt for Kill Switch, IEEE Spectrum 2008

- Increasing threat to hardware due to globalization
- Extremely difficult to detect kill switches (utilized by enemies to damage/destroy opponent artillery during critical missions) as well as intentional backdoors (to enable remote control of chips without user knowledge), which may have huge consequences
- Example: Syrian's Radar during Israeli attack, French Government using kill switches intentionally as a form of active defense to damage the chips if they fall in hostile hands, and more...



# Example Attack

## Fake Cisco routers risk "IT subversion"

- An internal Federal Bureau of Investigation presentation states that counterfeit Cisco routers imported from China may cause unexpected failures in American networks. The equipment could also leave secure systems open to attack through hidden backdoors.
- \$76 million **fake Cisco routers**
- **STILL HAPPENS TO A THIS DAY (MODCHIPS)**



## Energy Theft Going From Bad to Worse

- Tampering with “smart” meters
  - Oil, electricity, gas, ...
- \$1B loss in CT because of electricity theft



# Example Attack

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## Energy Theft Going From Bad to Worse

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# Example Attack

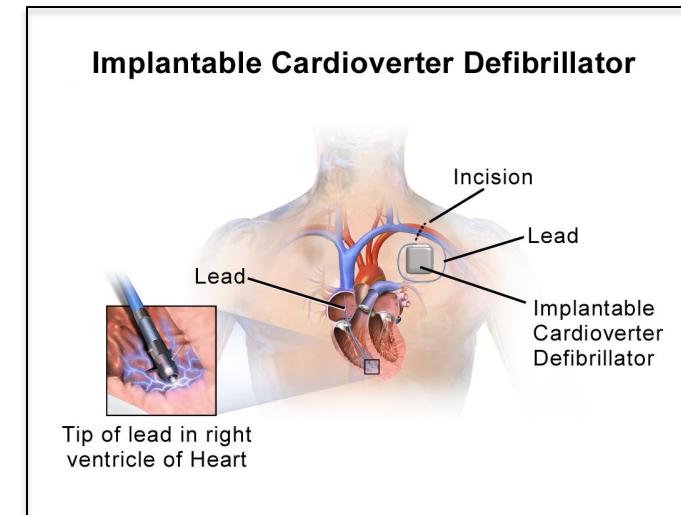
## The deadly world of fake medicine – CNN.com

- A **counterfeit medication** or a counterfeit drug is a medication or pharmaceutical product which is produced and sold with the intent to deceptively represent its origin, authenticity or effectiveness.



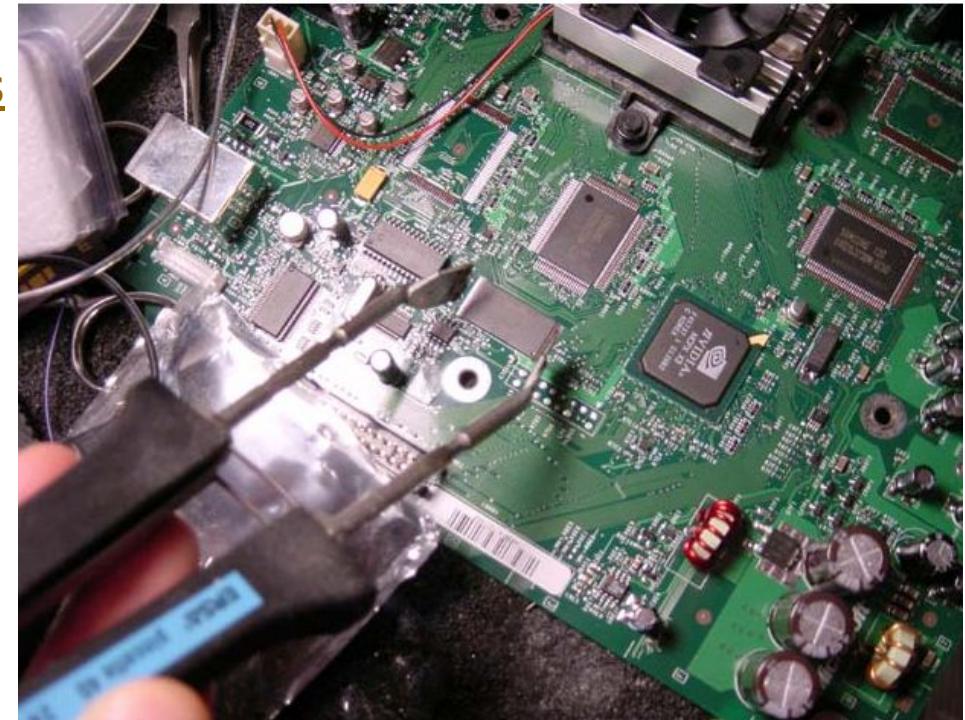
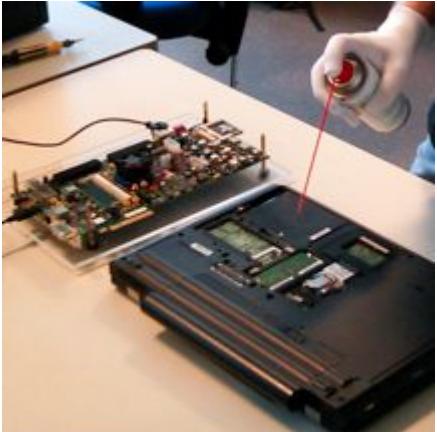
## Medical Device Security

- Incorporating security is sometimes considered expensive
- Implantable devices: e.g., Heart rate monitor
  - Incorporating Security could potentially reduce the life-time of the device by 30%
  - Attacking these device could result in loss of lives



# Example Attack

- **Hacking the XBOX**
  - <https://youtu.be/U7VwtOrwceo?t=310>
  - Must Watch!
- **Cold Boot**
  - <https://www.wired.com/story/siemens-s-7-1500-logic-controller-flaw/>
  - <https://youtu.be/nTvIQDe0rQU?t=2269>



# Example Attack

## Physical Attacks on Chip IDs

- Extracting secret keys

## Side-Channel Attacks

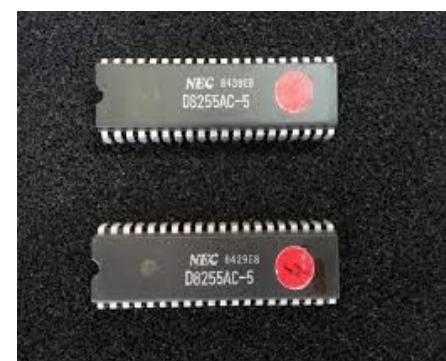
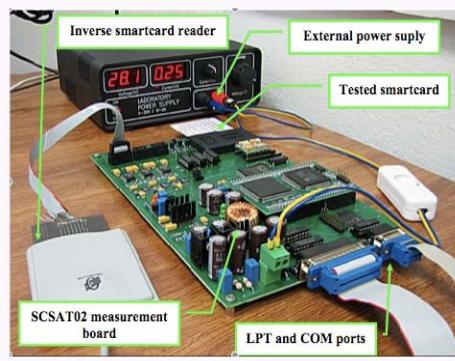
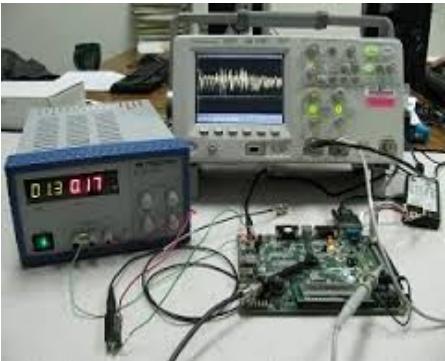
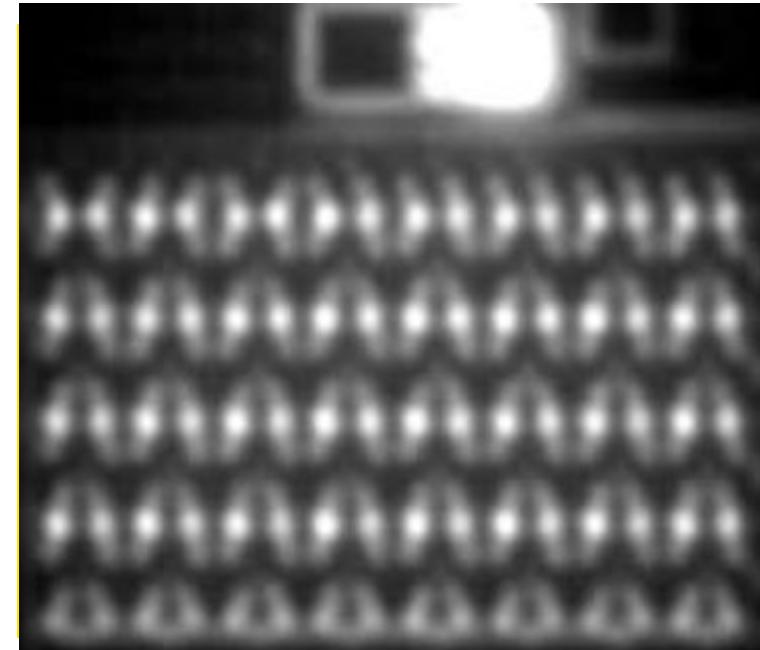
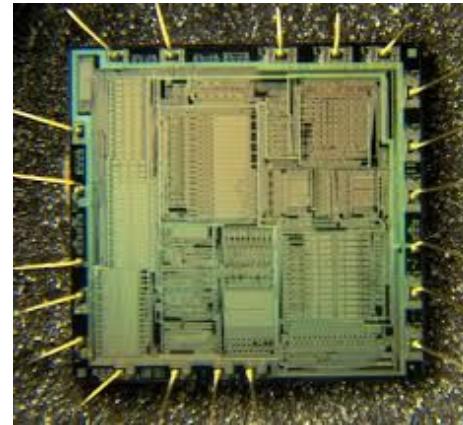
- Power Analysis, Timing Analysis, EM Analysis

## Tampering with Electronic Devices

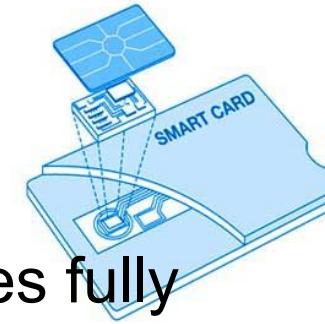
- Captured Drone by Iran

## Counterfeit Integrated Circuits

- Multi-billion dollar business



# Time for Smart Cards



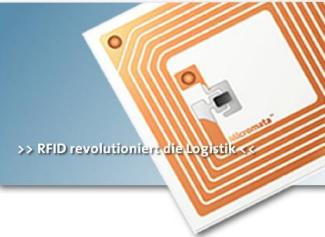
- By the end of 2006, Western European countries fully migrated to smart cards
  - Voting: In Sweden you can vote with your smart card, which serves as a non-repudiation device
  - Telecommunications: Many cellular phones come with smart cards in Europe and will soon be shipping in the United States.
  - Mass Transit: British Air relies on rail and air connections more than most airports.
- In 2006, ~27M contactless cards were in circulation in US, the number is estimated to top 100M by 2011
  - E.g., homeland security has required the port workers to have smart ID cards (Jan, 2007)
  - Entertainment: Most DSS (Digital Satellite Service) dishes in the U.S. have smart cards.

# Smart Cards -- Attacks



- Access Control: Smart Cards Under Attack - Literally,  
Ken Warren, Security Magazine, 03/17/2006
- Keep Your Enemies Close: Distance Bounding Against  
Smartcard Relay Attacks, Saar Drimer and Steven J. Murdoch, USENIX SECURITY, 2007
- Vulnerability Is Discovered In Security for Smart Cards,  
John Markoff, NY TIMES, 05/13/2002

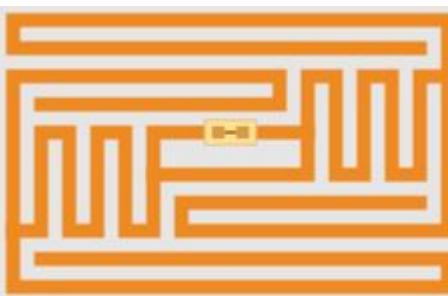
# RFIDs



**Radio-frequency identification (RFID)** is the use of an object (typically referred to as an RFID tag) applied to or incorporated into a product, animal, or person for the purpose of identification and tracking using radio waves.

**Most RFID tags contain at least two parts:**

- An integrated circuit for storing and processing information, modulating and demodulating a radio-frequency (RF) signal, and other specialized functions.
- An antenna for receiving and transmitting the signal.
- Some are active (battery) and some others are passive



# RFIDs



- Many applications in securing transactions,
  - Inventory Control Container / Pallet Tracking
  - ID Badges and Access Control
  - Fleet Maintenance Equipment/Personnel Tracking in Hospitals
  - Parking Lot Access and Control
  - Car Tracking in Rental Lots
  - Product Tracking through Manufacturing and Assembly
- Challenge: Can we create security mechanisms light enough to be suitable for the RFIDs?

# Piracy – Some True Stories...

---

- In 2000, Chen Jin, finished Ph.D. in computer engineering at UT Austin
  - He went back to China, first to Motorola research and then to Jiaotong University as a faculty
  - In 2003, he supervised a team that created one of China's first homegrown DSP IC
  - Chen was named one of China's brightest young scientists, funded his own lab, got a huge grant from the government
  - In 2006, it was revealed that he faked the chip, stealing the design from Texas Instruments!
  - Links to the article: [1](#), [2](#)
-

# The Athens Affair

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- In March 8, 2005, Costas Tsalikidis, a 38-year-old Engineer working for Vodafone Greece committed suicide – linked to the scandal!
- The next day, the prime minister got notified that his cell phone – and those of many other high-rank officials – were hacked!
- Earlier in Jan, investigators had found rogue software installed on the Vodafone Greece by parties unknown
- The scheme did not depend on the wireless nature
- A breach in keeping keys in a file – Vodafone was fined €76 million December 2006!

# Interesting Articles

---

- **The Hunt for the Kill Switch**, IEEE Spectrum, May 2008
  - J. Villasenor and M. Tehranipoor, "**The Hidden Dangers of Chop Shop Electronics**" IEEE Spectrum, Sep. 2013.
  - M. Tehranipoor, U. Guin, and S. Bhunia, "**Invasion of the Hardware Snatchers: Fake Hardware Could Open the Door to Malicious Malware and Critical Failure**," IEEE Spectrum, 2017.
  - S. Quadir, J. Chen, D. Forte, N. Asadi, S. Shahbaz, L. Wang, J. Chandy, and M. Tehranipoor, "**A Survey on Chip to System Reverse Engineering**," ACM Journal on Emerging Technologies in Computing Systems (JETC), 2015.
  - M. Alam, M. Tehranipoor, and U. Guin, "**TSensors Vision, Infrastructure, and Security Challenges in Trillion Sensor Era**," Journal of Hardware and Systems Security (HaSS), 2017.
  - K. Yang, H. Shen, D. Forte, S. Bhunia, and M. Tehranipoor, "**Hardware-Enabled Pharmaceutical Supply Chain Security**," ACM Transactions on Design Automation of Electronic Systems (TODAES), 2017.
  - F. Rahman, B. Shakya, X. Xu, D. Forte, and M. Tehranipoor, "**Security Beyond CMOS: Fundamentals, Applications, and Roadmap**," IEEE Transactions on VLSI (TVLSI), 2017.
-



Meltdown



Spectre

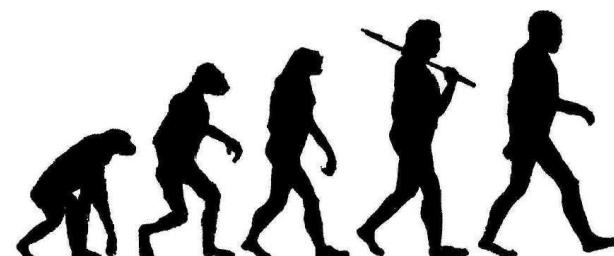
## **Zero-Click iPhone Exploit (Crazy):**

[https://googleprojectzero.blogspot.com/2021/12/a-deep-dive-int  
o-nso-zero-click.html](https://googleprojectzero.blogspot.com/2021/12/a-deep-dive-int-o-nso-zero-click.html)

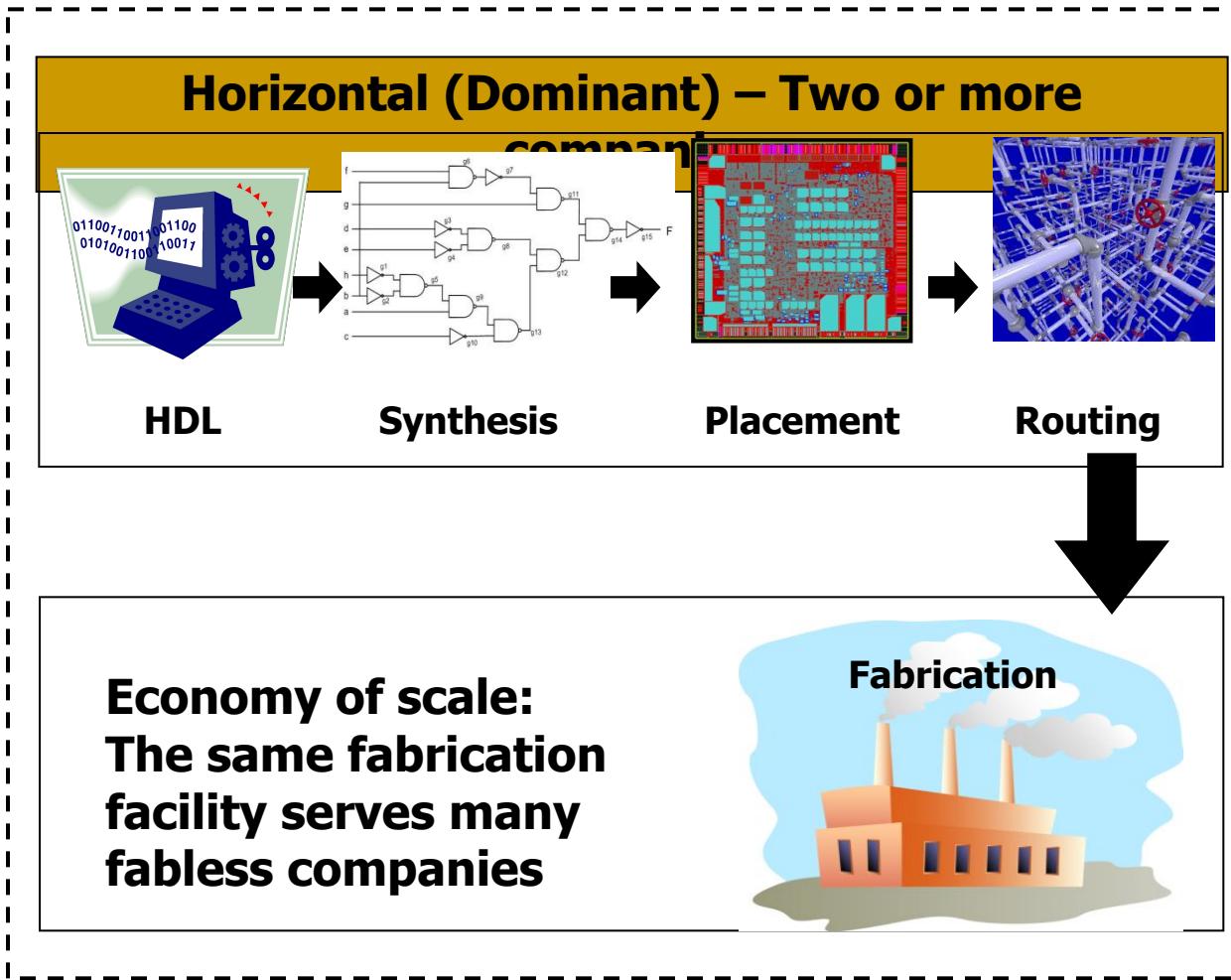
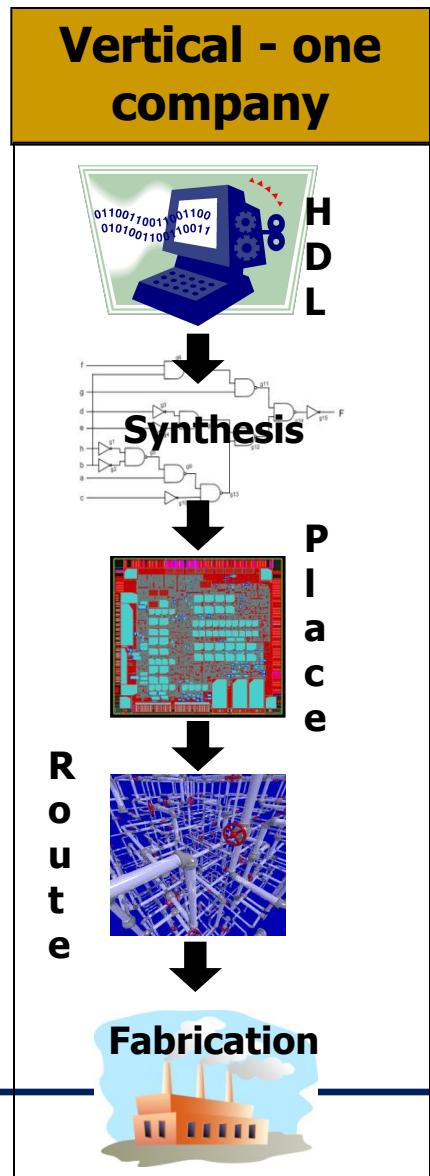
# Evolution of Hardware Security and Trust

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- **Prior to 1996:** Coating, encapsulation, labeling, taping, ... still many companies don't spend much for securing their hardware
- **1996:** Extracting secret keys using power analysis – started the side-channel signal analysis era
- **1998:** Hardware unique ID
- **2002:** Physically Unclonable Functions (PUFs), True Random Number Generation (TRNG), Hardware tagging New: <https://en.wikipedia.org/wiki/Lavarand>
- **2004-2007:** DARPA TRUST, Hardware trust
- **2008:** DARPA IRIS Program – Reverse engineering, tampering, and reliability
- **2008:** Counterfeit ICs
- **2012:** Senate Armed Services – National Defense Authorization Act (NDAA) 2012
- **2014:** DARPA SHIELD – Supply chain security
- **2015:** DARPA LADS
- More...

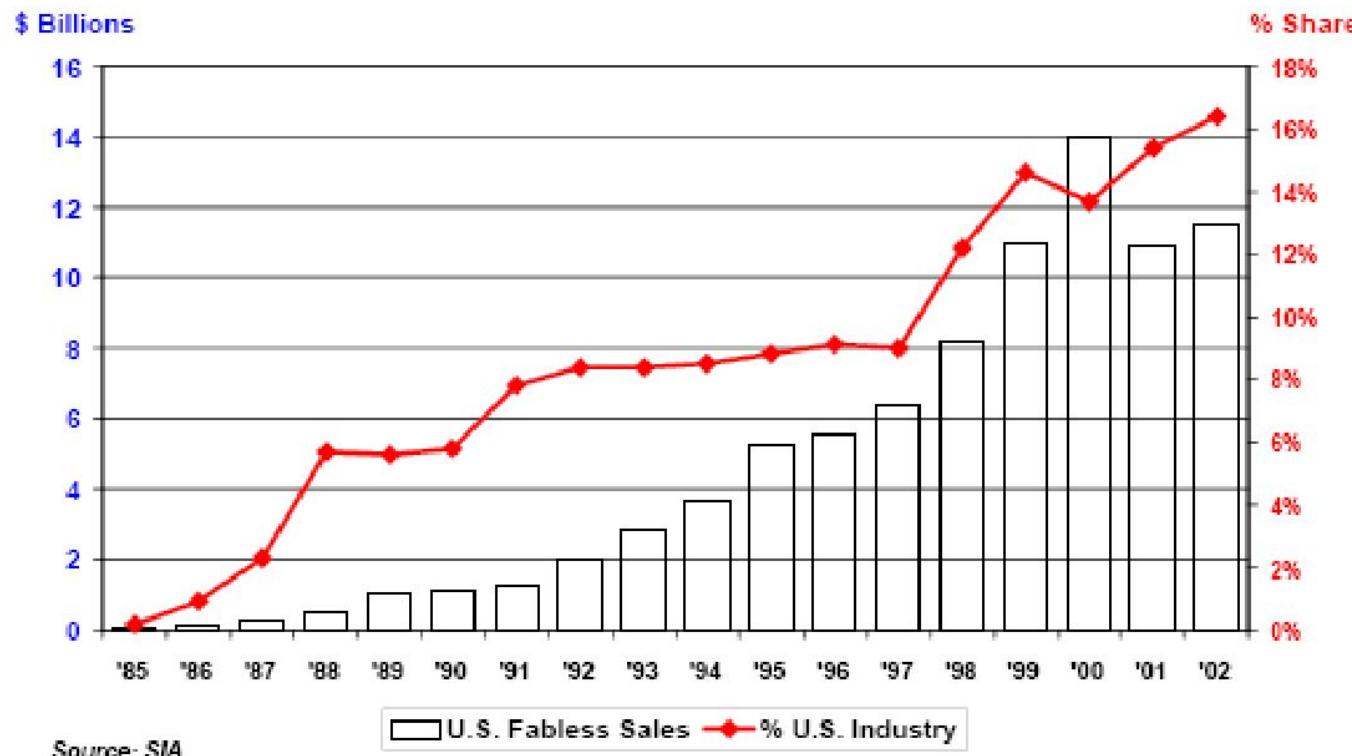


# Shift in the Industry's Business Model



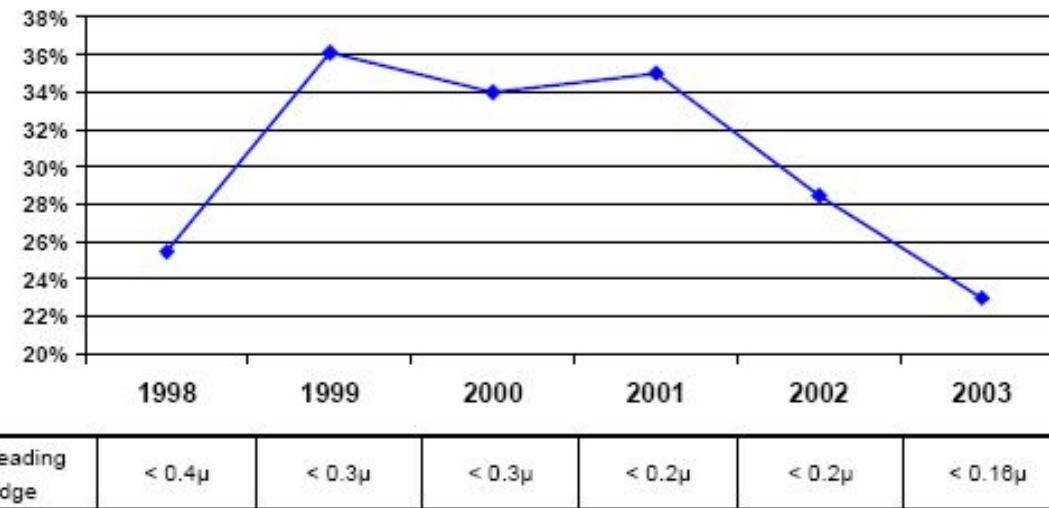
# Microelectronic Industry Business Model

The fabless/foundry business model has grown to 16% of the U.S. chip industry. The trend is strongest in the leading process technology portion of the industry



# Leading-Edge Technology

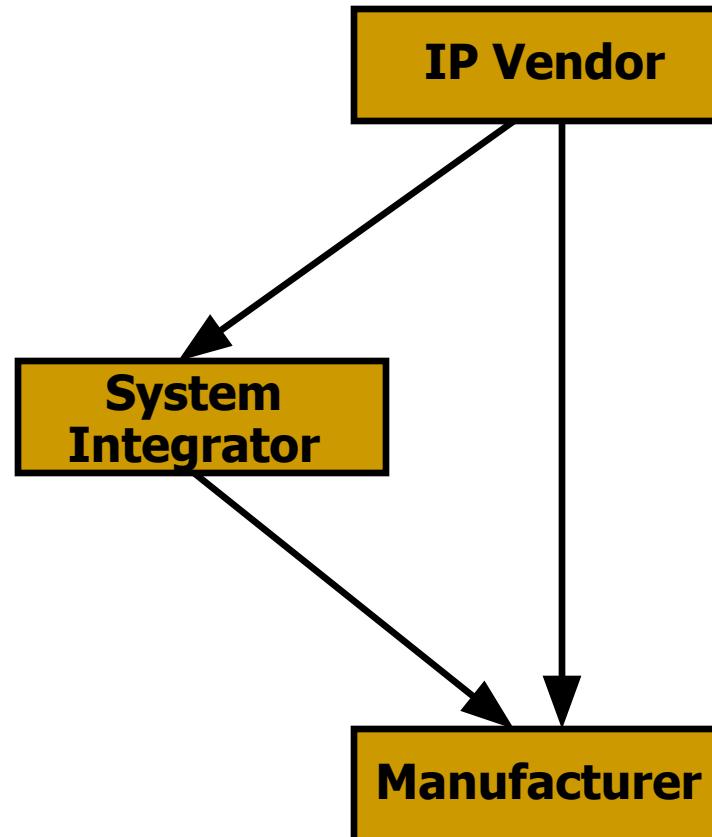
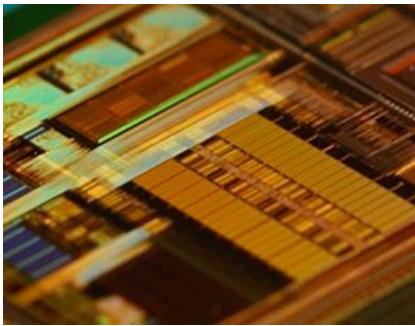
U.S. industry's share of capital expenditures falling and in leading edge semiconductor manufacturing capacity.



Source: SICAS/SIA

- The cost of building a full-scale, 300 mm wafer 65nm process chip fabrication plant is about \$3bn
- How much does a modern fab cost? [Hint: a lot]

# HW Threats

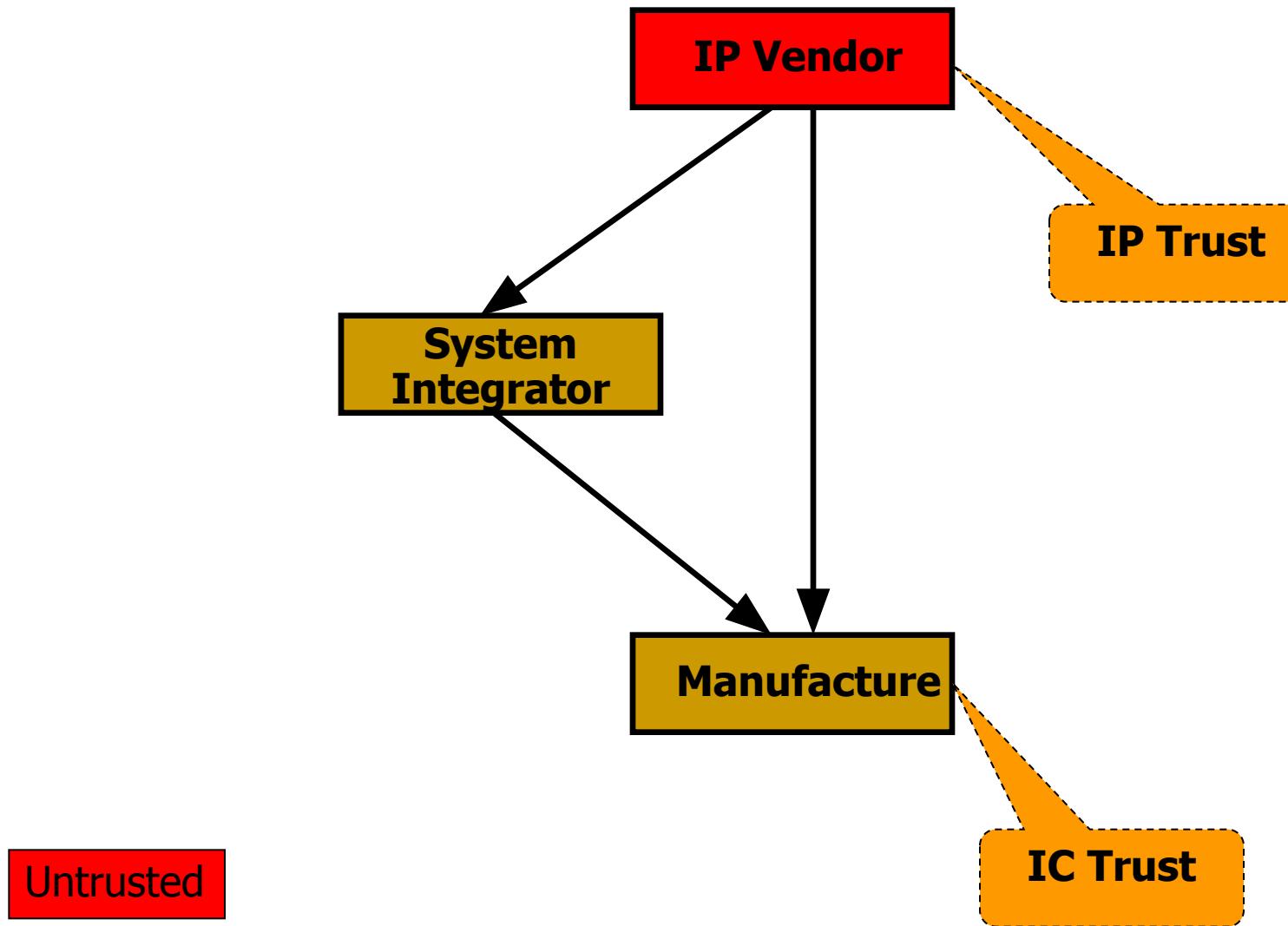


```
OR2X1 U1468 (.IN1(n1317), .IN2(g45), .ON(n1347));  
NOR2X0 U1469 (.IN1(p31), .IN2(g41), .IN4(g46), .IN4(n1449), .ON(n1319));  
INVX8 U1470 (.IN1(n1317), .IN2(n1351), .ON(n1347));  
INVX8 U1471 (.INP(g44), .ZN(n1351));  
NAND2X1 U1472 (.IN1(n1319), .IN2(1889), .ON(n1317));  
NAND2X2 U1473 (.IN1(g44), .IN2(g43), .ON(n1336));  
OR2X1 U1474 (.IN1(n1333), .IN2(g448), .ON(n1351));  
NOR2X0 U1475 (.IN1(g45), .IN2(n1329), .ON(n1447));  
INVX8 U1476 (.INP(g46), .ZN(n1459));  
NAND2X1 U1477 (.IN1(n1486), .IN2(1485), .ON(n1494));  
NOR2X0 U1478 (.IN1(g1972), .IN2(18664), .ON(n1437));  
NOR2X0 U1479 (.IN1(n1317), .IN2(n1322), .ON(n1325));  
INVX8 U1480 (.INP(g47), .ZN(n1336), .IN3(n1335), .ON(n1359));  
INVX8 U1481 (.INP(g48), .ZN(n1449));  
NAND2X1 U1482 (.IN1(g48), .IN2(n1886), .ON(n1324));  
NAND2X2 U1483 (.IN1(g45), .IN2(n1887), .ON(n1322));  
NAND2X2 U1484 (.IN1(n1327), .IN2(1348), .ON(n1349));  
NOR2X0 U1485 (.IN1(n1511), .IN2(n1347), .ON(n1327));  
INVX8 U1486 (.INP(g43), .ZN(n1348));  
NAND2X1 U1487 (.IN1(g47), .IN2(n1319), .ON(n1343));  
NOR2X0 U1488 (.IN1(g1868), .IN2(n1591), .ON(n1646));  
INVX8 U1489 (.INP(g1696), .ZN(n1460));  
OR2X0 U1490 (.IN1(n1705), .IN2(n1793), .ON(n1788));
```

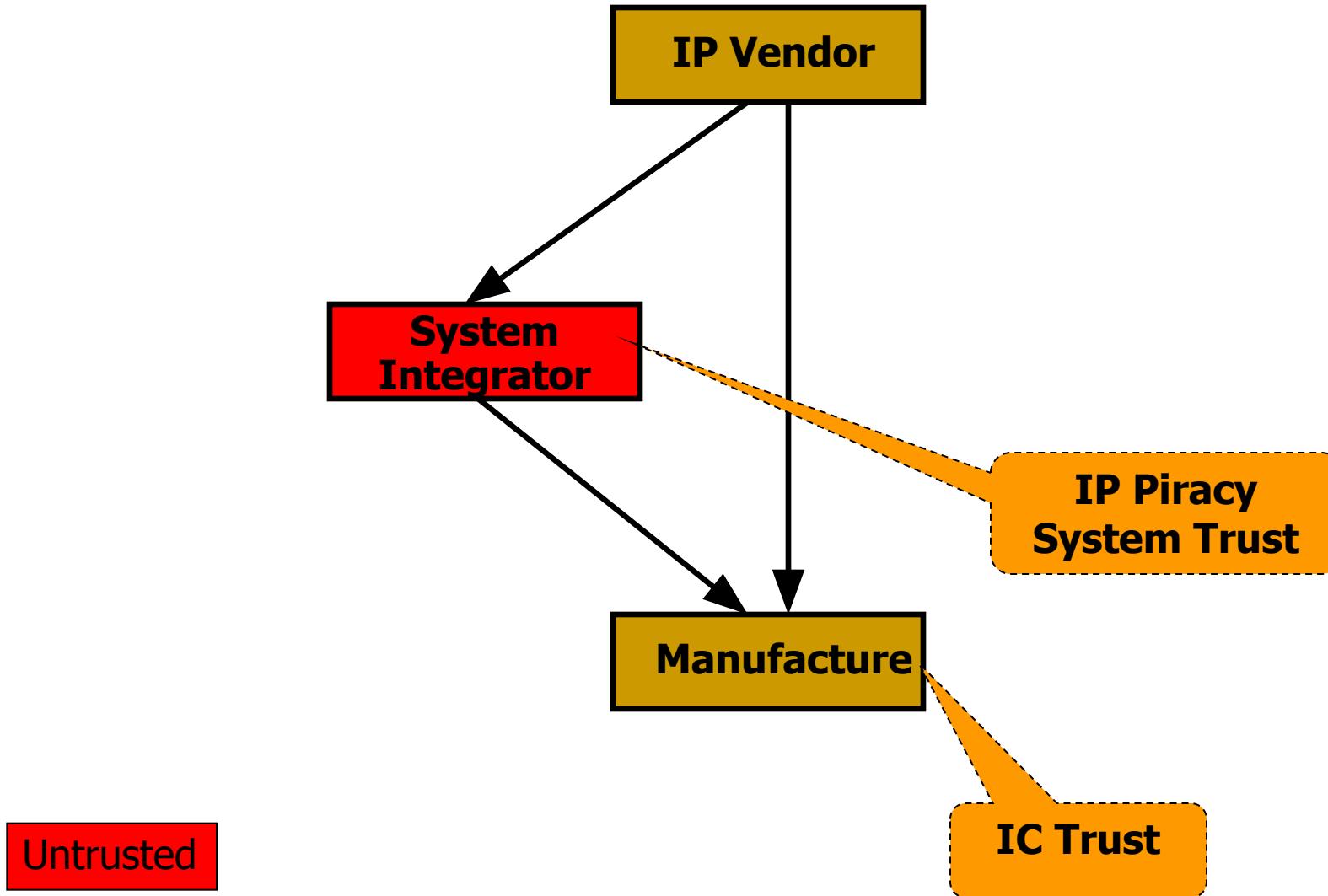


Any of these steps can be untrusted

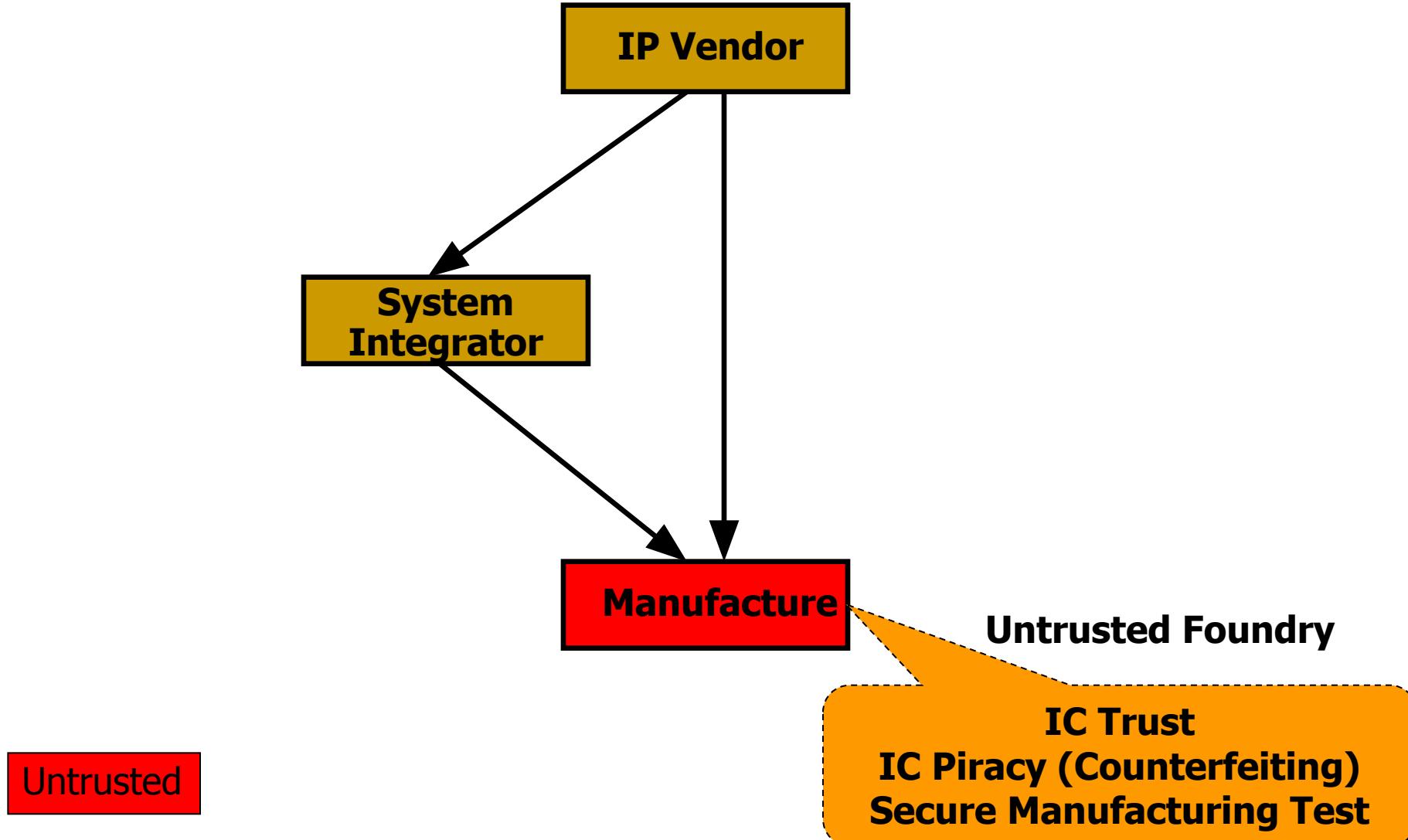
# HW Threats



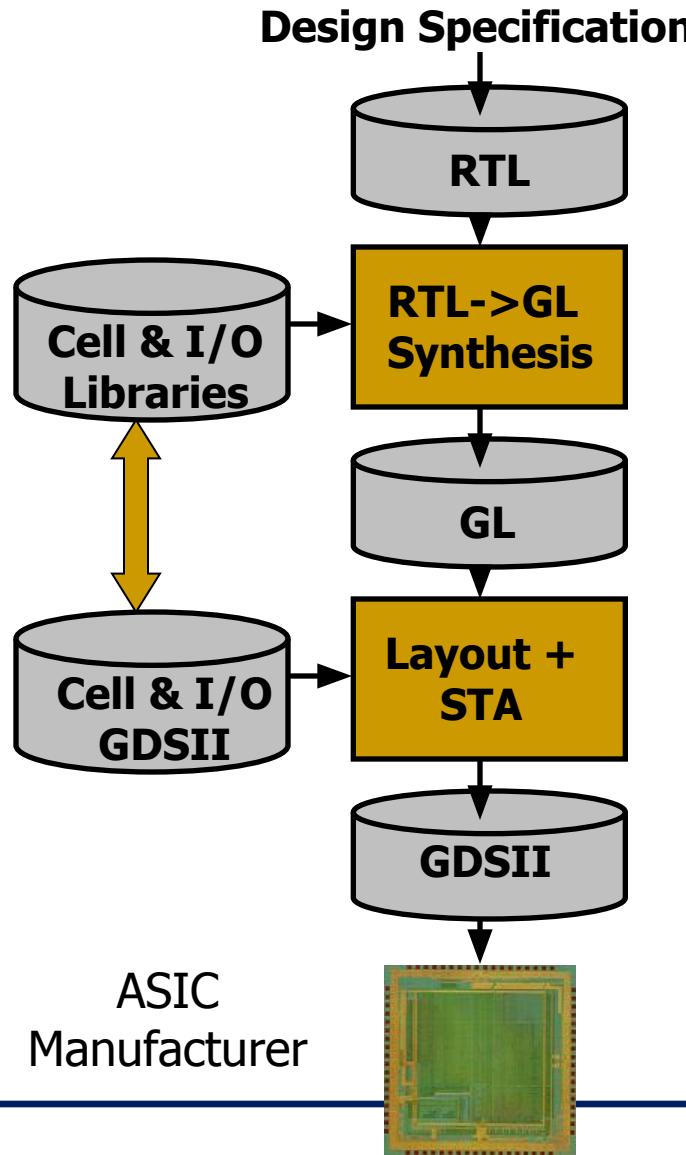
# HW Threats



# HW Threats

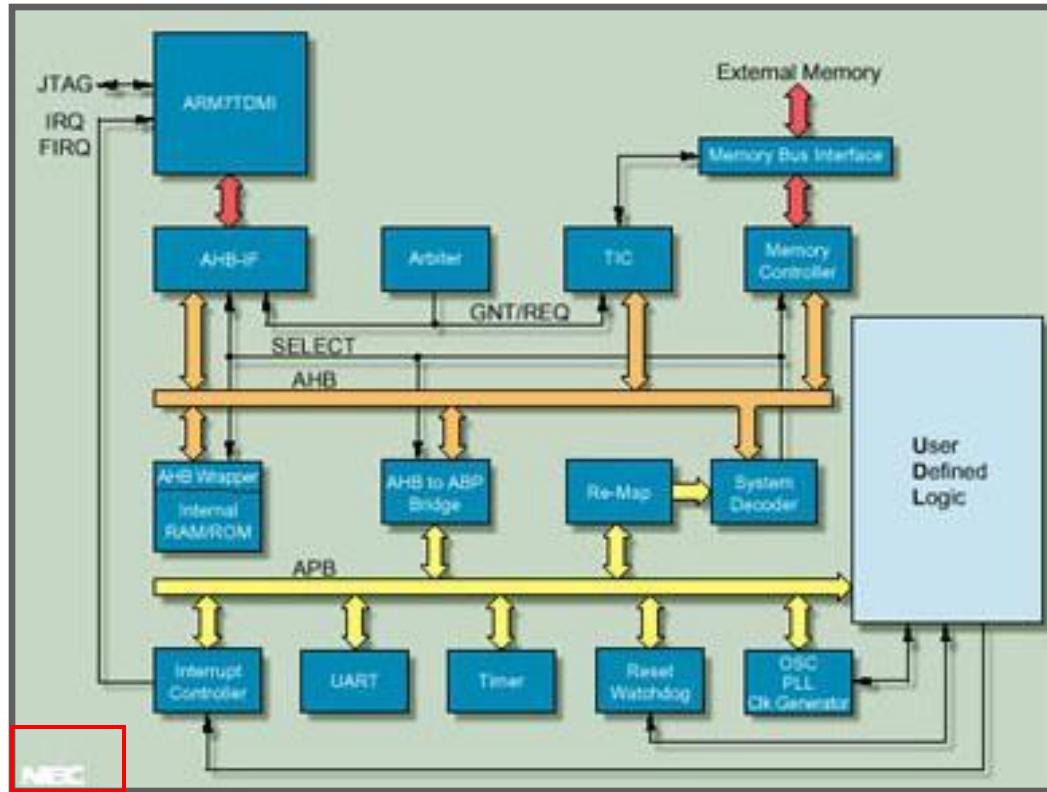


# Design Process – Old Way

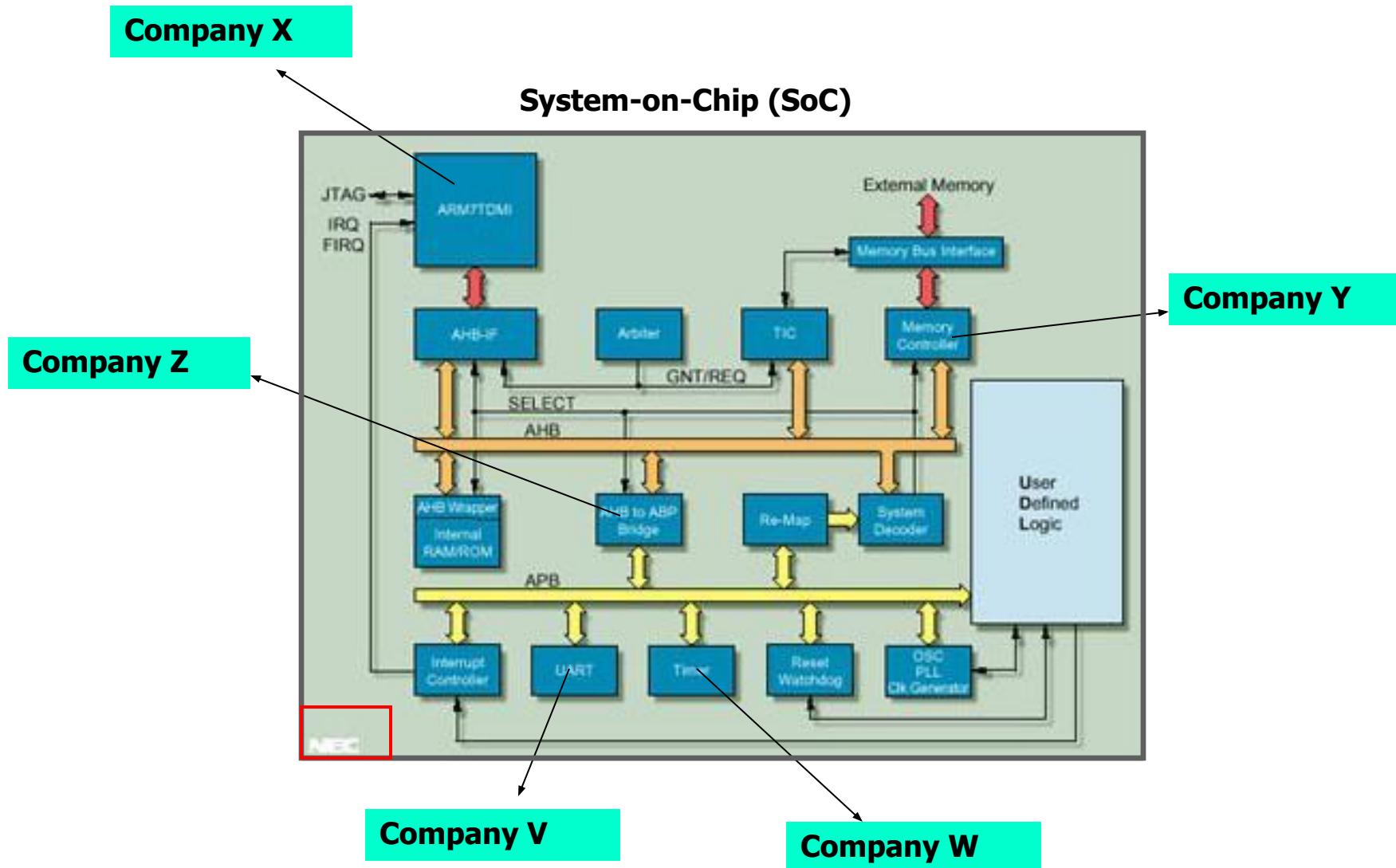


# Issues with Third-Party IP Design

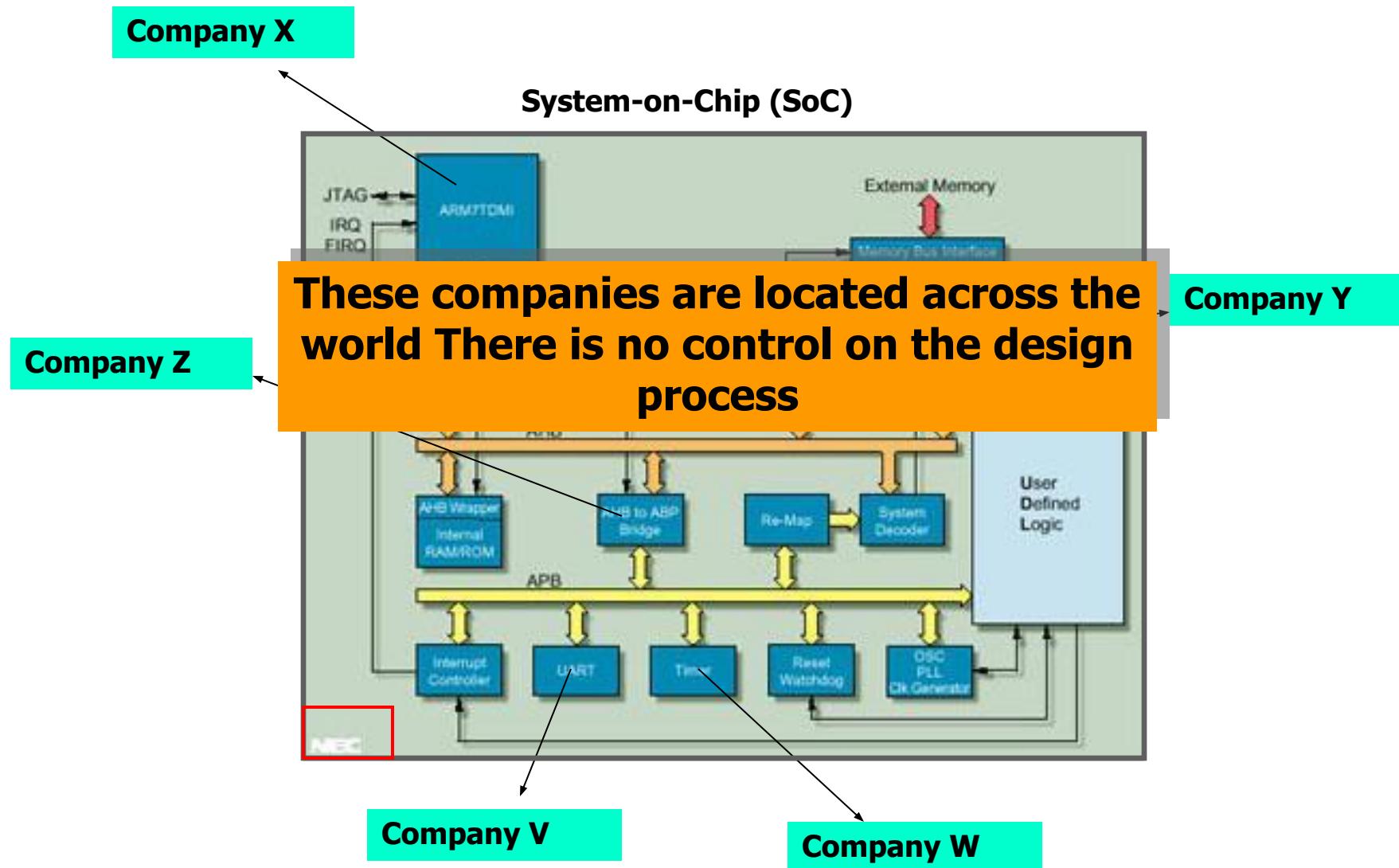
System-on-Chip (SoC)



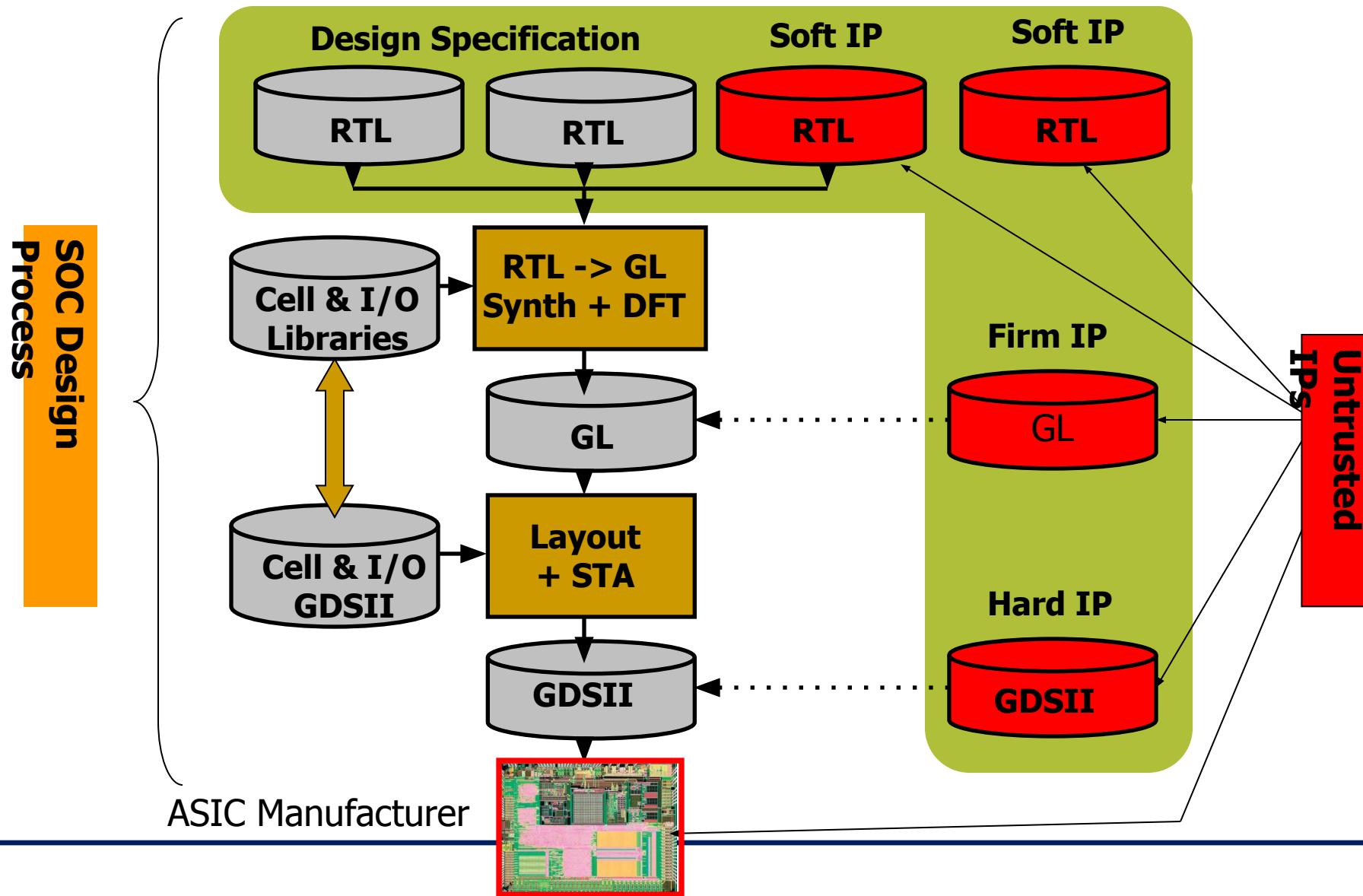
# Issues with Third-Party IP Design



# Issues with Third-Party IP Design



# Design Process – New Way



# **Who Develops the IPs? Who Designs the ICs? Who Fabricates Them?**

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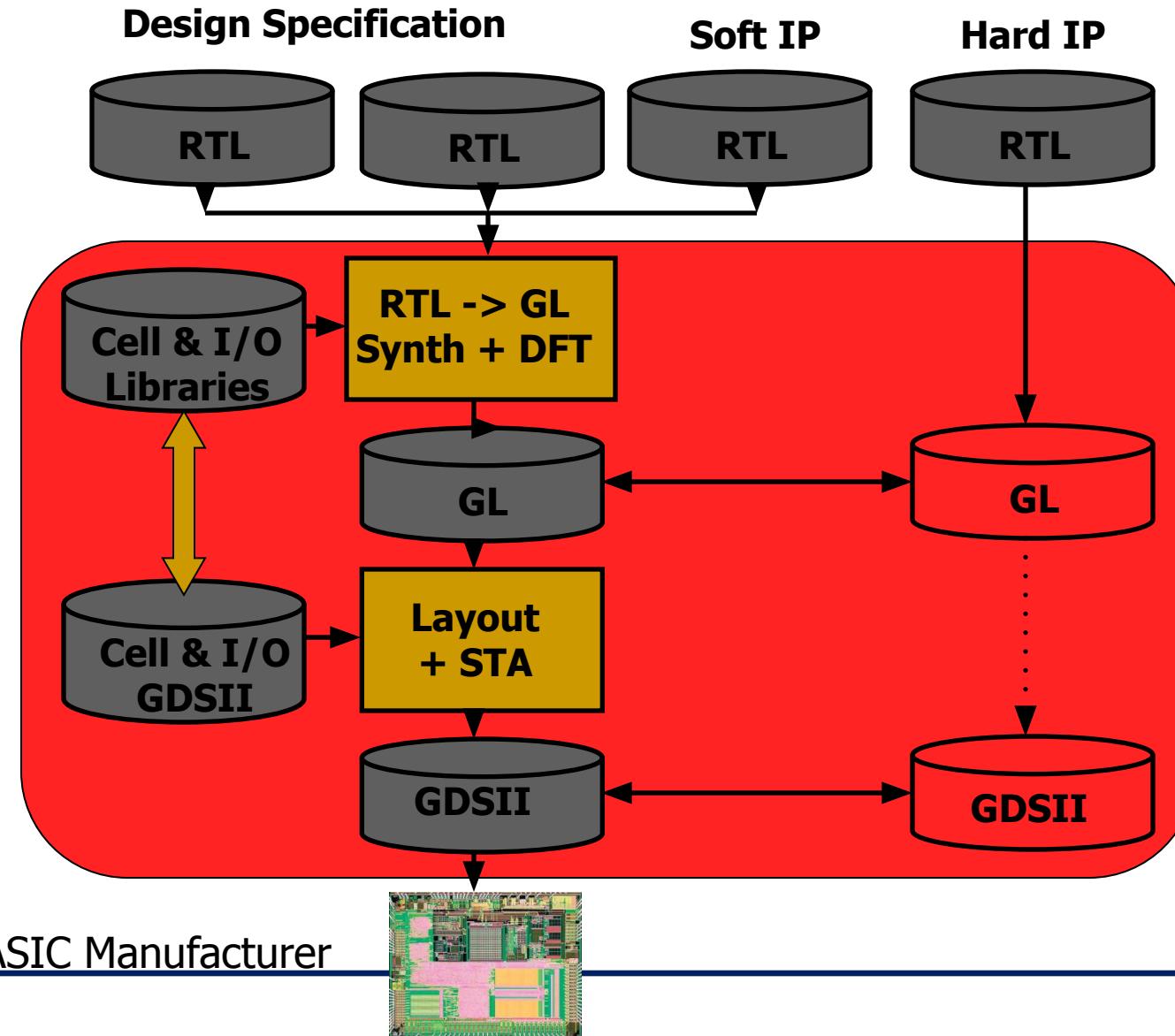


# Who Develops the IPs? Who Designs the ICs? Who Fabricates Them?

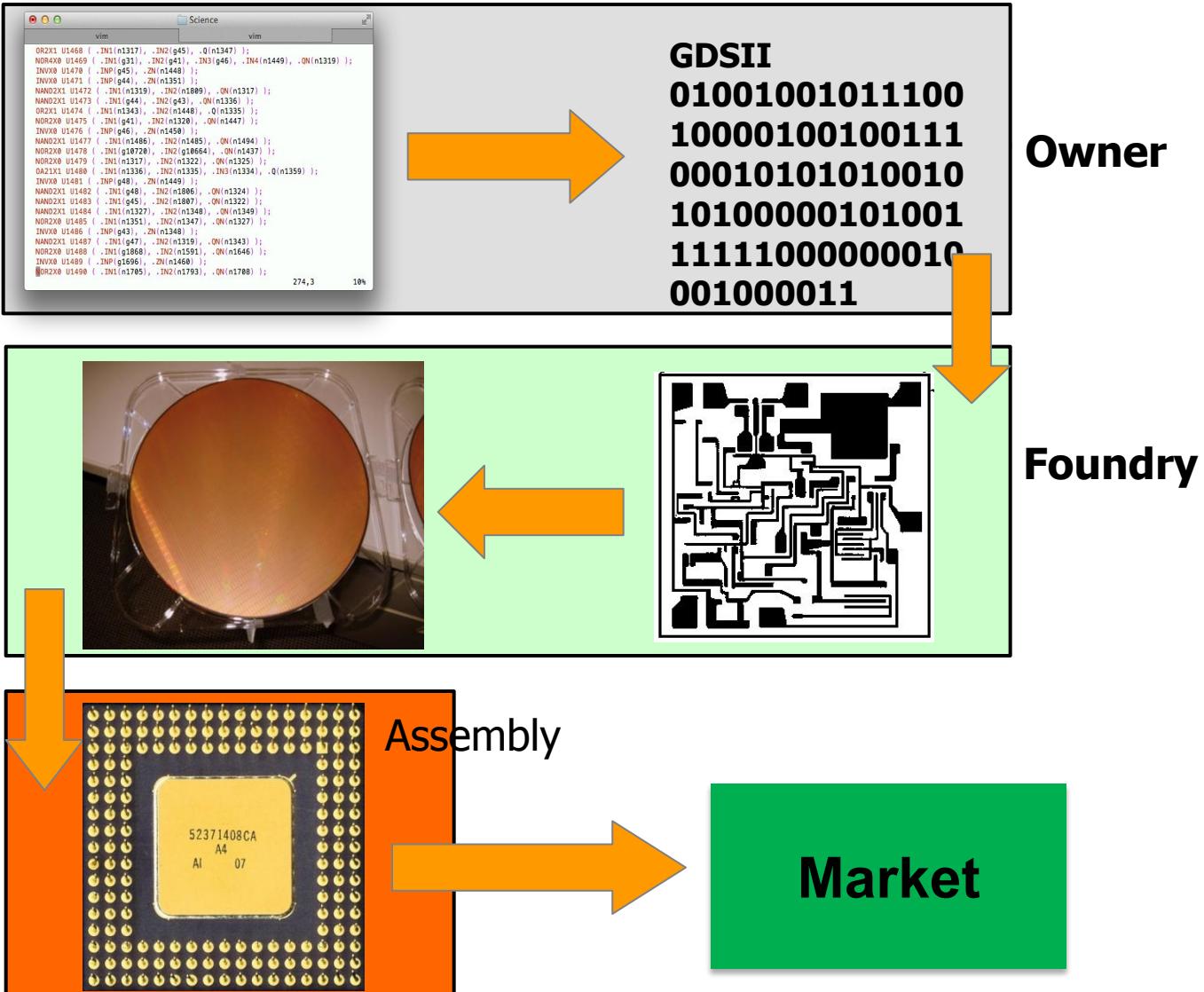
*Every Where!*



# Untrusted System Integrator

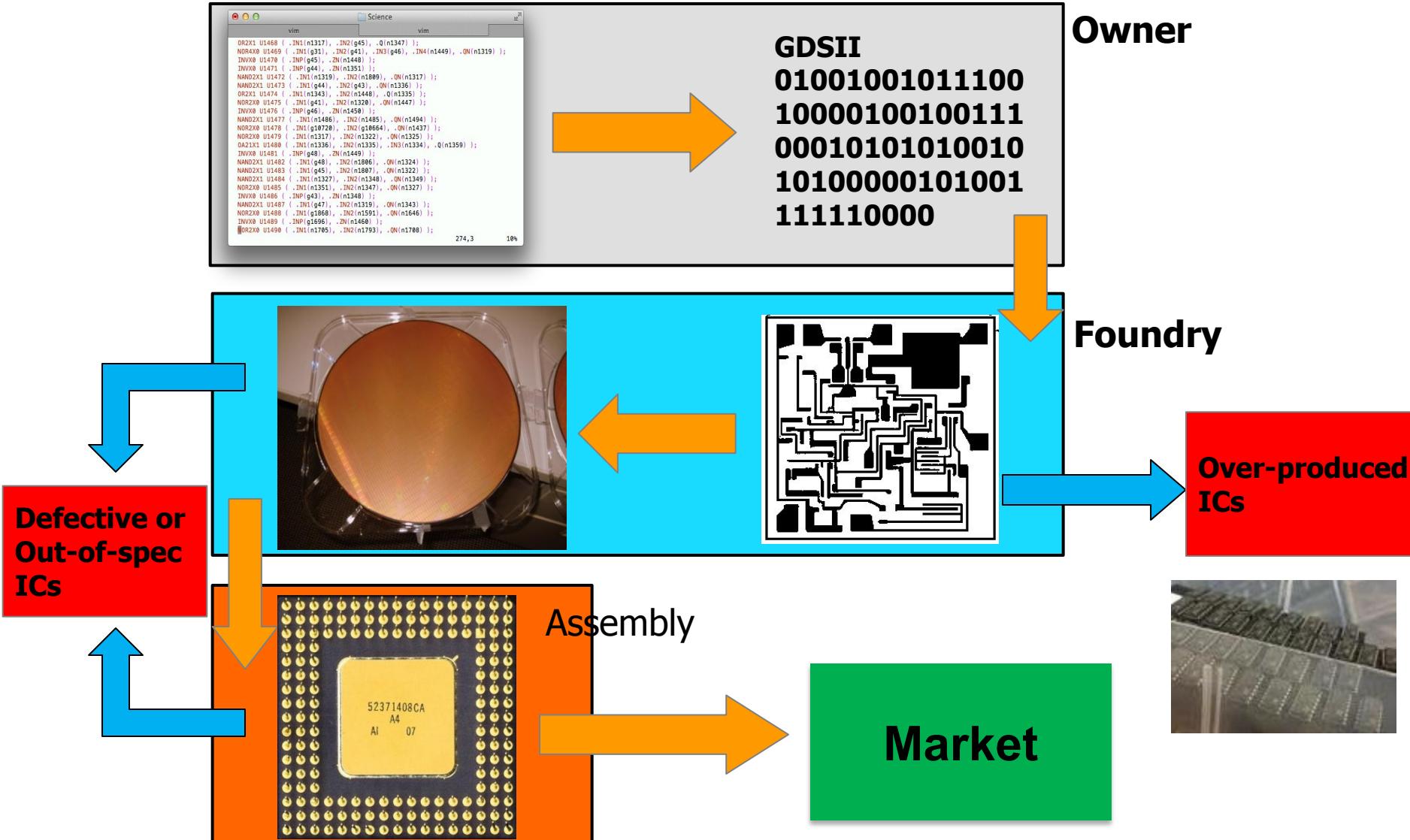


# Counterfeiting



Google image

# Counterfeiting



Google image

# IC Counterfeiting

- Most prevalent attack today
- Unauthorized production of wafers
- It is estimated that counterfeiting is costing semiconductor industry more than several billion dollars per year



Over production

Defective parts

Off-spec parts

Cloned ICs

Recycled ICs

# IC Recycling Process

A recycling center



PCBs taken off of  
electronic systems



ICs taken off of PCBs

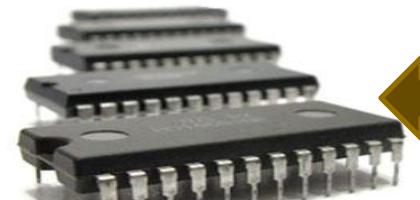


Critical Application



<https://www.youtube.com/watch?v=leFuF-zoVzA>  
FUN WATCH

Resold as new



Refine recycled ICs

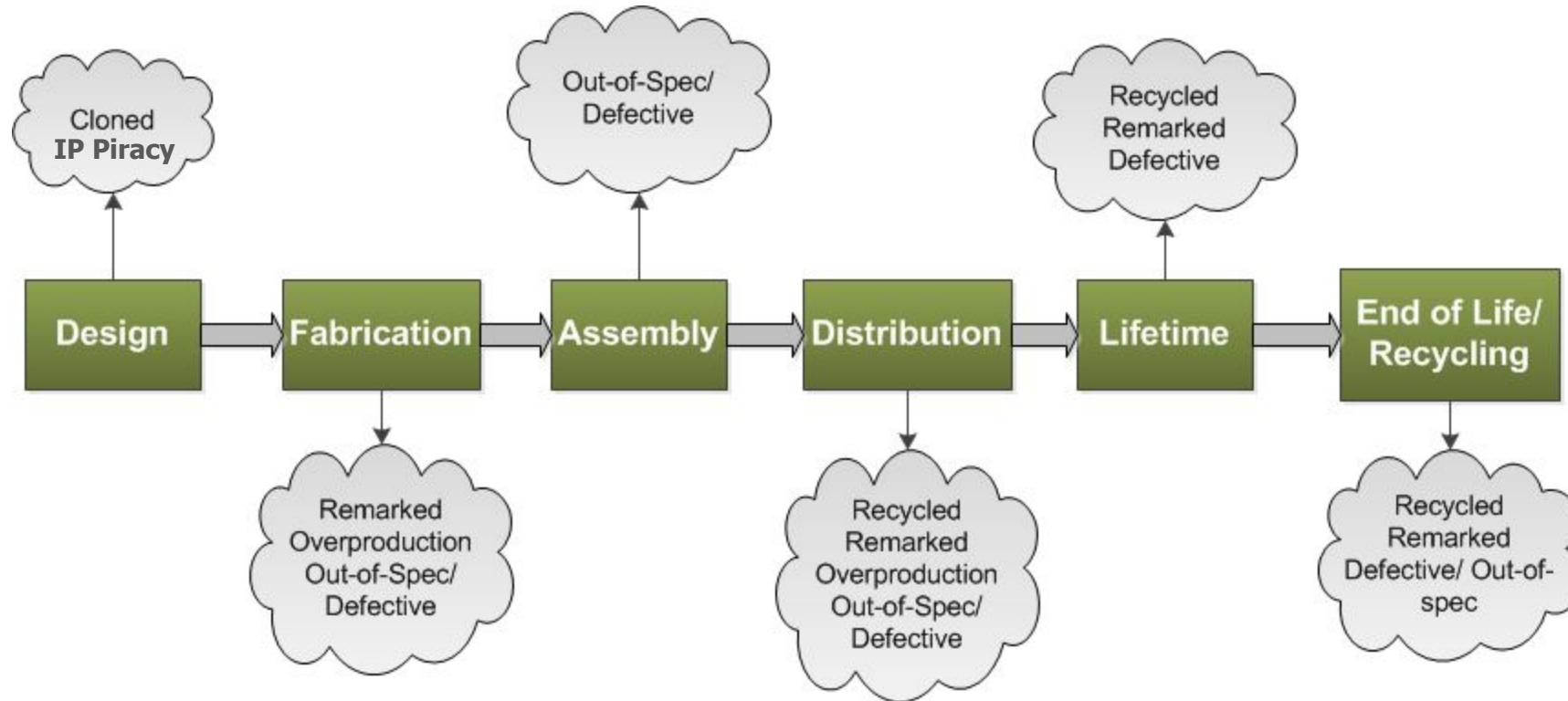


**Identical:**  
Appearance, Function, Specification

**Consumer trends suggest that more gadgets are used in much shorter time – more e-waste**

Source: Images are taken from google

# Supply Chain Vulnerabilities



# Some Basic Definitions

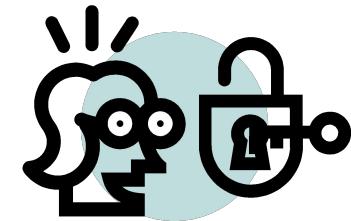
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- **Intellectual property** represents the property of your mind or intellect
  - proprietary knowledge
- The four legally defined forms of IP
  - **Patents** When you register your invention with the government, you gain the legal right to exclude anyone else from manufacturing or marketing it
  - **Trademarks** A trademark is a name, phrase, sound or symbol used in association with services or products
  - **Copyrights** Copyright laws protect written or artistic expressions fixed in a tangible medium
  - **Trade secrets** A formula, pattern, device or compilation of data that grants the user an advantage over competitors

# Some Basic Definitions (Cont'd)

## ■ Cryptography:

- crypto (secret) + graph (writing)
  - the science of locks and keys
- The keys and locks are mathematical
- Underlying every security mechanism, there is a “secret”...
  
- We are going to talk some about the traditional crypto, but we will also show new forms of security based on other forms of HW-based secret



# What Does Secure Mean?

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- It has to do with an asset that has some value – think of what can be an asset!
- There is no static definition for “secure”
- Depends on what is that you are protecting your asset from
- Protection may be sophisticated and unsophisticated
- Typically, breach of one security makes the protection agent aware of its shortcoming



# Typical Cycle in Securing a System

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- Predict potential breaches and vulnerabilities
- Consider possible countermeasures, or controls
- Either actively pursue identifying a new breach, or wait for a breach to happen
- Identify the breach and work out a protected system again



# Computer Security

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- No matter how sophisticated the protection system is – simple breaches could break-in
- A computing system is a collection of hardware (HW), software (SW), storage media, data, and human interacting with them
- Security of SW, data, and communication
- HW security, is important and challenging
  - Manufactured ICs are obscure
  - HW is the platform running SW, storage and data
  - Tampering can be conducted at many levels
  - Easy to modify because of its physical nature

---

EVERYTHING IS BREAKABLE

# Definitions



- **Vulnerability:** Weakness in the secure system
- **Threat:** Set of circumstances that has the potential to cause loss or harm
- **Attack:** The act of a human exploiting the vulnerability in the system
- **Computer security aspects**
  - **Confidentiality:** the related assets are only accessed by authorized parties
  - **Integrity:** the asset is only modified by authorized parties
  - **Availability:** the asset is accessible to authorized parties at appropriate times

# Hardware Vulnerabilities

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- Physical Attacks
- Trojan Horses
- IP Piracy
- IC Piracy & Counterfeiting
- Backdoors
- Tampering
- Reverse Engineering
- Exploiting Flaws/Bugs



# Adversaries

- **Individual, group or governments**
  - Pirating the IPs – illegal use of IPs
  - Inserting backdoors, or malicious circuitries
  - Implementing Trojan horses
  - Reverse engineering of ICs
  - Spying by exploiting IC vulnerabilities
- **System integrators**
  - Pirating the IPs
- **Fabrication facilities**
  - Pirating the IPs
  - Pirating the ICs
- **Counterfeiting parties**
  - Recycling, cloned, etc.



# Hardware Controls for Secure Systems

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- Hardware implementations of encryption
  - Encryption has to do with scrambling to hide
- Design locks or physical locks limiting the access
- Devices to verify the user identities
- Hiding signatures in the design files
- Intrusion detection
- Hardware boards limiting memory access
- Tamper resistant
- Policies and procedures
- More ...



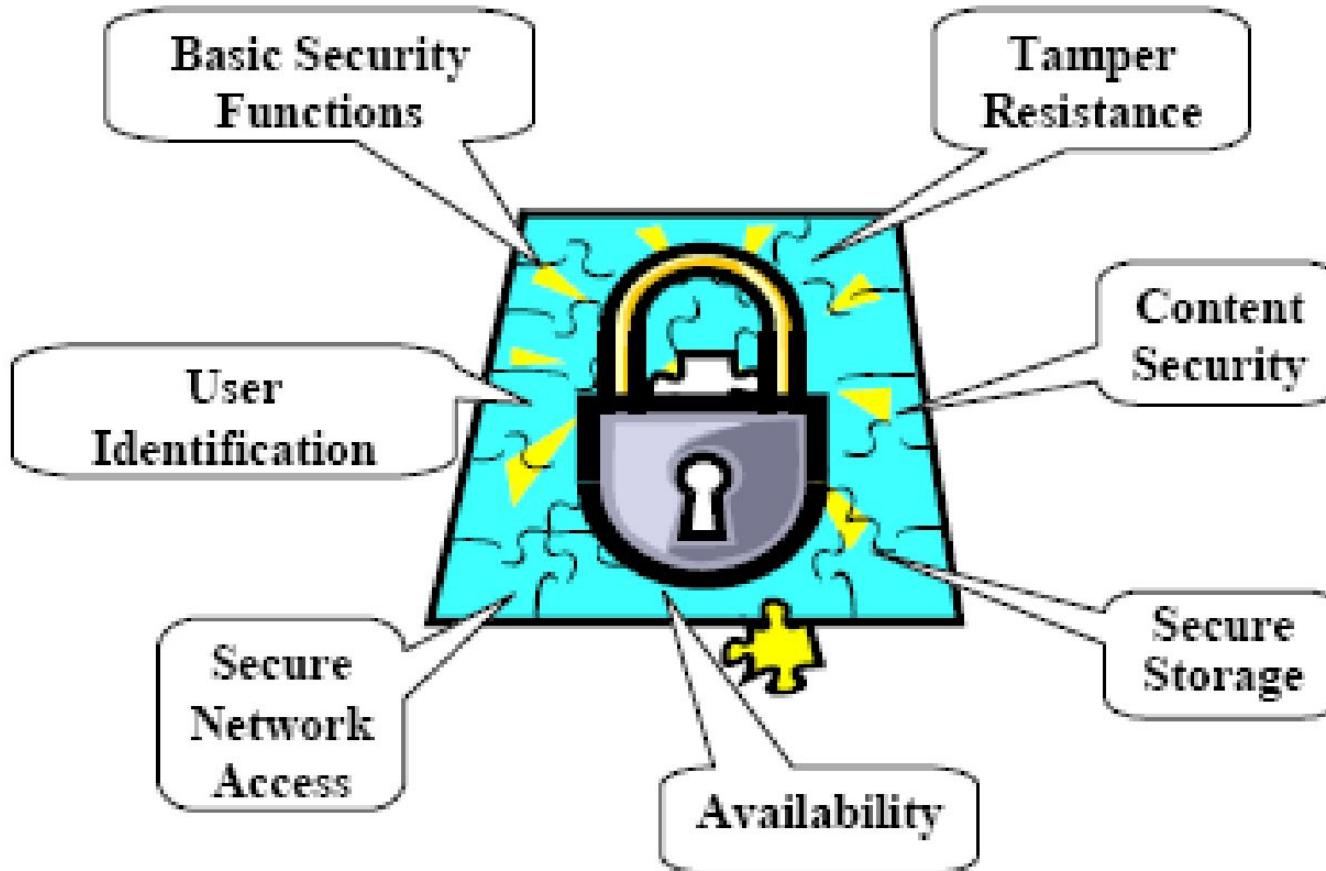
# Embedded Systems Security/IoTs

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- Security processing adds overhead
    - Performance and power
  - Security is challenging in embedded systems/IoTs
    - Size and power constraints, and operation in harsh environments
  - Security processing may easily overwhelm the other aspects of the system
  - Security has become a new design challenge that must be considered at the design time, along with other metrics, i.e., cost, power, area
-

# Security Requirements in the IoT Era

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# Secure Embedded Systems - Design Challenges

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- Processing gap
  - Battery gap
  - Flexibility
    - Multiple security objectives
    - Interoperability in different environments
    - Security processing in different layers
  - Tamper resistance
  - Assurance gap
  - Cost
-

- **Underlying most security mechanisms or protocols is the notion of a “secret”**
    - Lock and keys
    - Passwords
    - Hidden signs and procedures
    - Physically hidden
-

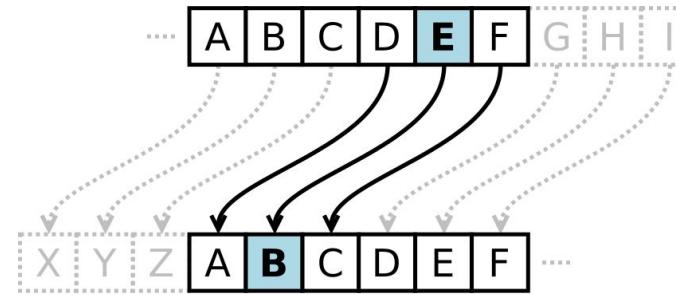
# Cryptography – History

- Has been around for 2000+ years
- In 513 B.C, Histiaeus of Miletus, shaved the slave's head, tattooed the message on it, let the hair grow



# Cryptography – Pencil & Paper Era

- Caesar's cipher: shifting each letter of the alphabet by a fixed amount!
  - Easy to break



Plaintext: THE QUICK BROWN FOX JUMPS OVER THE LAZY DOG

Ciphertext: QEB NRFZH YOLTQ CLU GRJMP LSBO QEB IXWV ALD

- Cryptoquote: simple substitution cipher, permutations of 26 letters
  - Using the dictionary and the frequencies, this is also easy to break

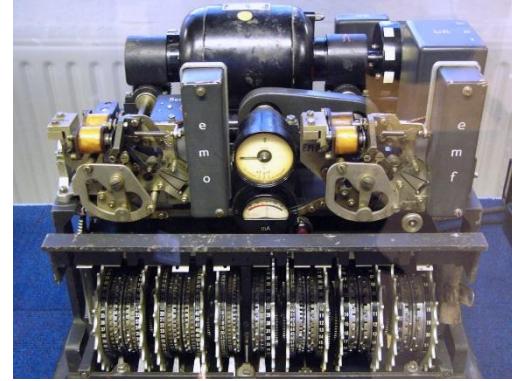
# Cryptography – Mechanical Era

- Around 1900, people realized cryptography has math and stat roots
- German's started a project to create a mechanical device to encrypt messages
- Enigma machine □ supposedly unbreakable
- A few polish mathematicians got a working copy
- The machine later sold to Britain, who hired 10,000 people to break the code!
- They did crack it! The German messages were transparent to enemies towards the end of war
  - Estimated that it cut the war length by about a year
- British kept it secret until the last working Enigma!



# Cryptography – Mechanical Era

- Another German-invented code was Tunny (Lorenz cipher system)
- Using a pseudorandom number generator, a seed produced a key stream  $ks$
- The key stream xor'd with plain text  $p$  to produce cipher  $c$ :  $c=p \oplus ks$
- How was this code cracked by British cryptographers at Bletchley Park in Jan 1942?
- A lucky coincidence!



German rotor stream cipher machines used by the German Army during World War II

# Cryptography – Modern Era

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- First major theoretical development in crypto after WWII was Shannon's Information Theory
  - Shannon introduced the one-time pad and presented theoretical analysis of the code
  - The modern era really started around 1970s
  - The development was mainly driven by banks and military system requirements
  - NIST developed a set of standards for the banks,
    - DES: Data Encryption Standard
-