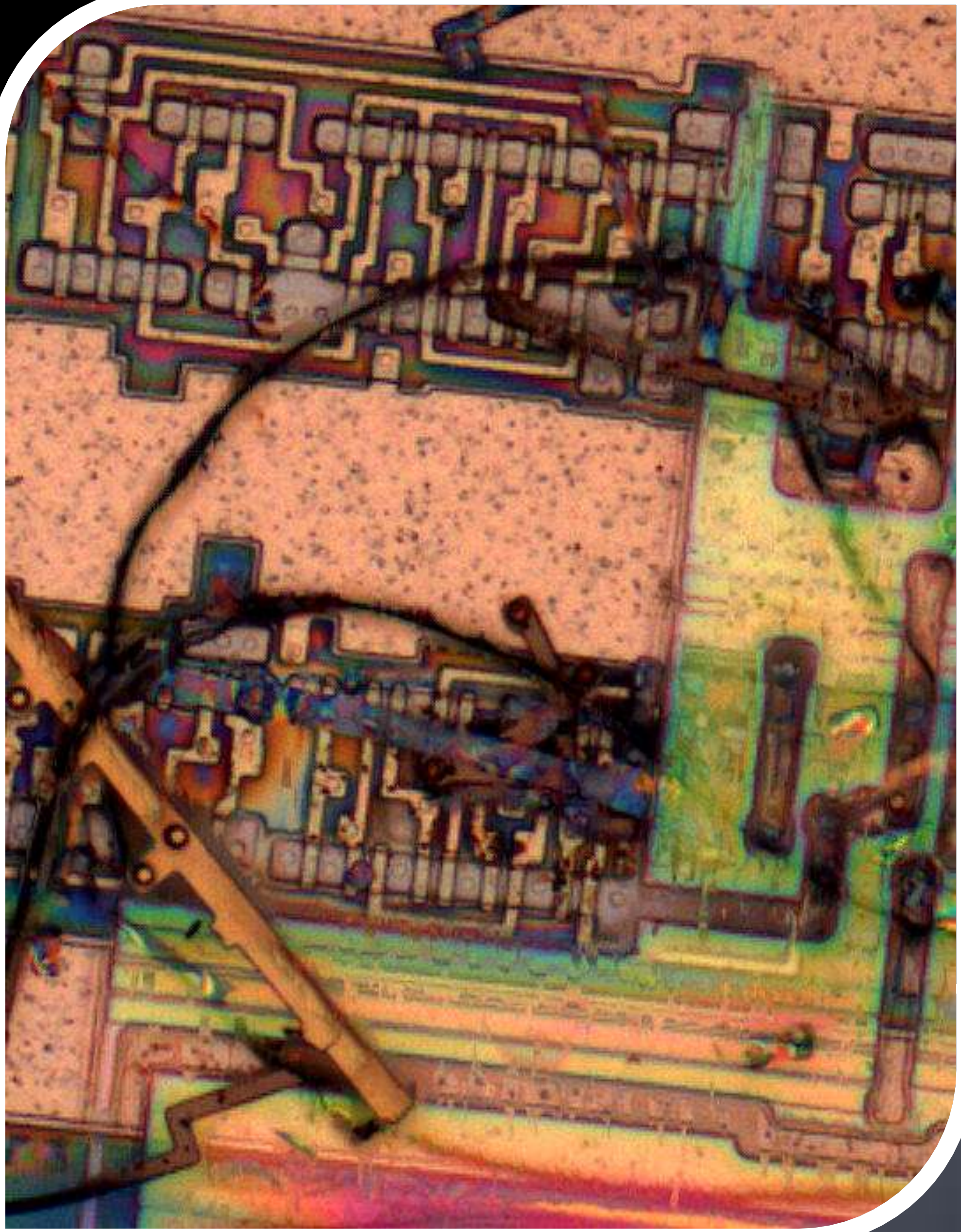
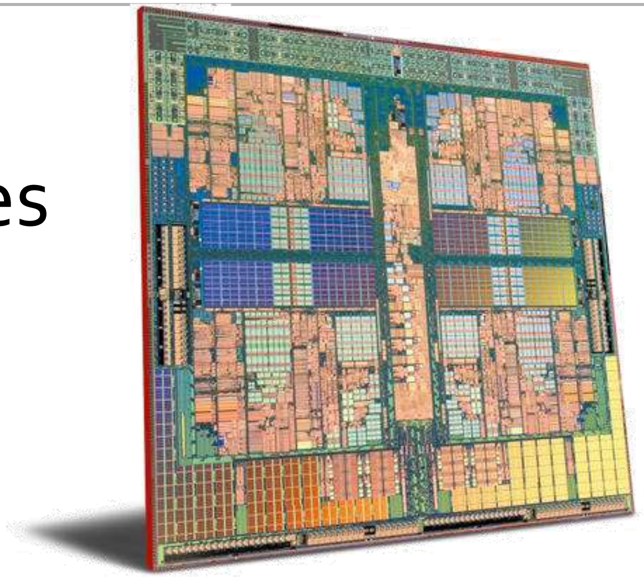
Hardware Reverse Engineering



Starbug & Karsten Nohl
University of Virginia

Summary



- Critical hardware relies on proprietary security primitives
  - These algorithms can easily be reverse-engineered
  - Their security level is often low
- When designing security, prepare for failure
  - Goal should be low risk of large damage, but not perfect security
  - Publicly reviewed algorithms and independent analysis yield best results

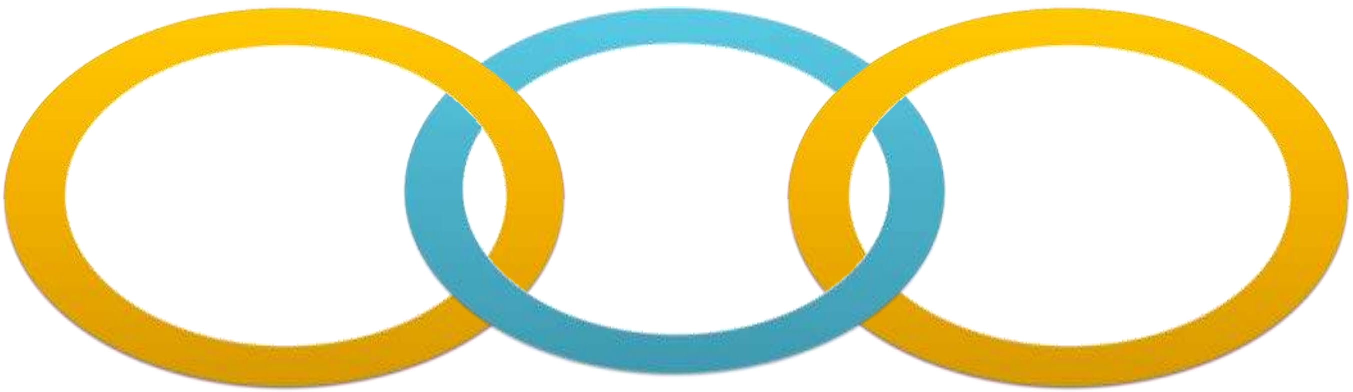
Motivation

- Lots of critical systems rely on secure hardware
  - Smartcards for access control, payment tokens
  - Also: satellite TV cards, car keys, printer cartridges, …
- Security often considered hard and expensive
  - Hence, often excluded from initial design
    - Protection added after problems arise
    - Patchwork security is harder and more expensive!

Finding security bugs in hardware systems becomes ever easier, threat grows.

Security Definition

- Security is a chain
  - Its strength is determined by the weakest link



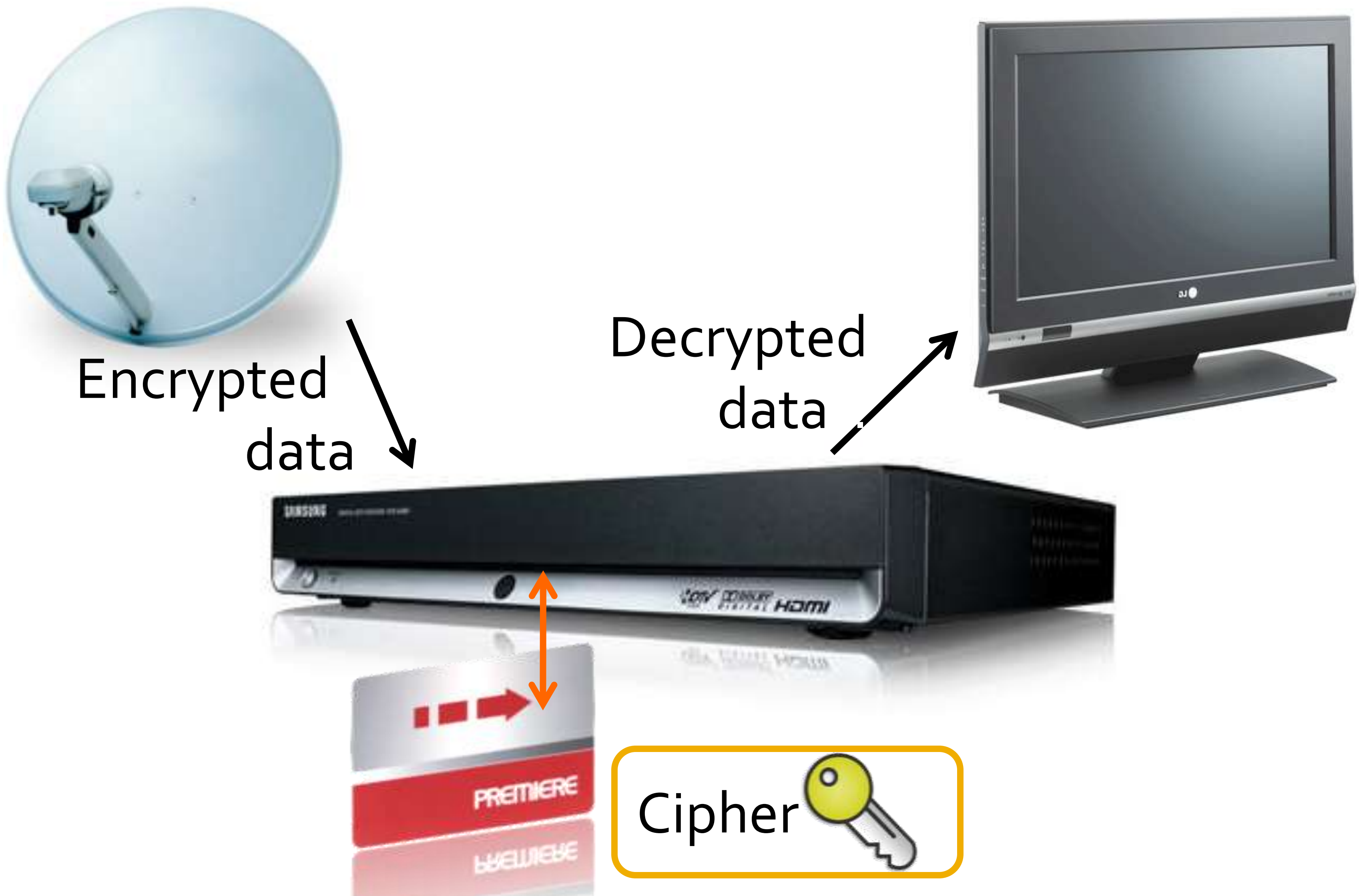
Example: Smart Cards

Cryptographic cipher

Challenge-response protocol

Cryptographic cipher

Example: Satellite TV



Foundation of Hardware Security

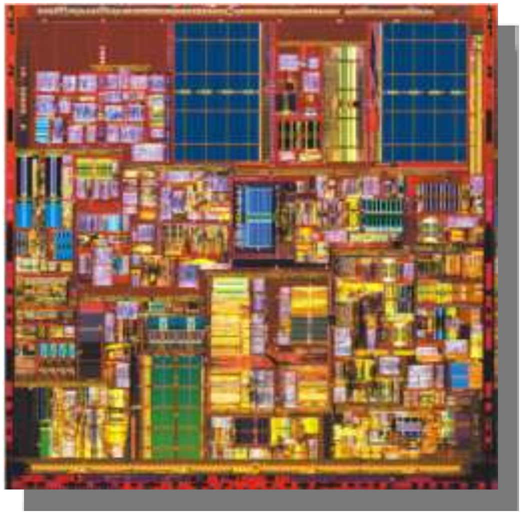
- Hardware security relies on
  a) Key storage
  b) Cryptographic cipher (encryption)

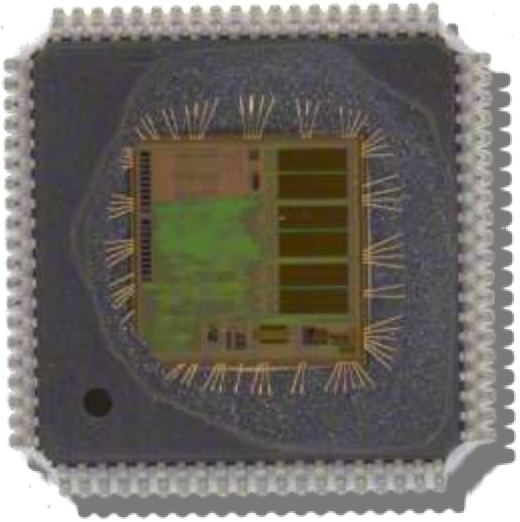
- Many systems fail to acknowledge lack of secrecy in hardware

> This talk discusses common weaknesses in secure key storage and proprietary encryption.

Outline

- Reverse-engineering secret algorithms
  1. Open chips
  2. Find structures
  3. Reconstruct circuit

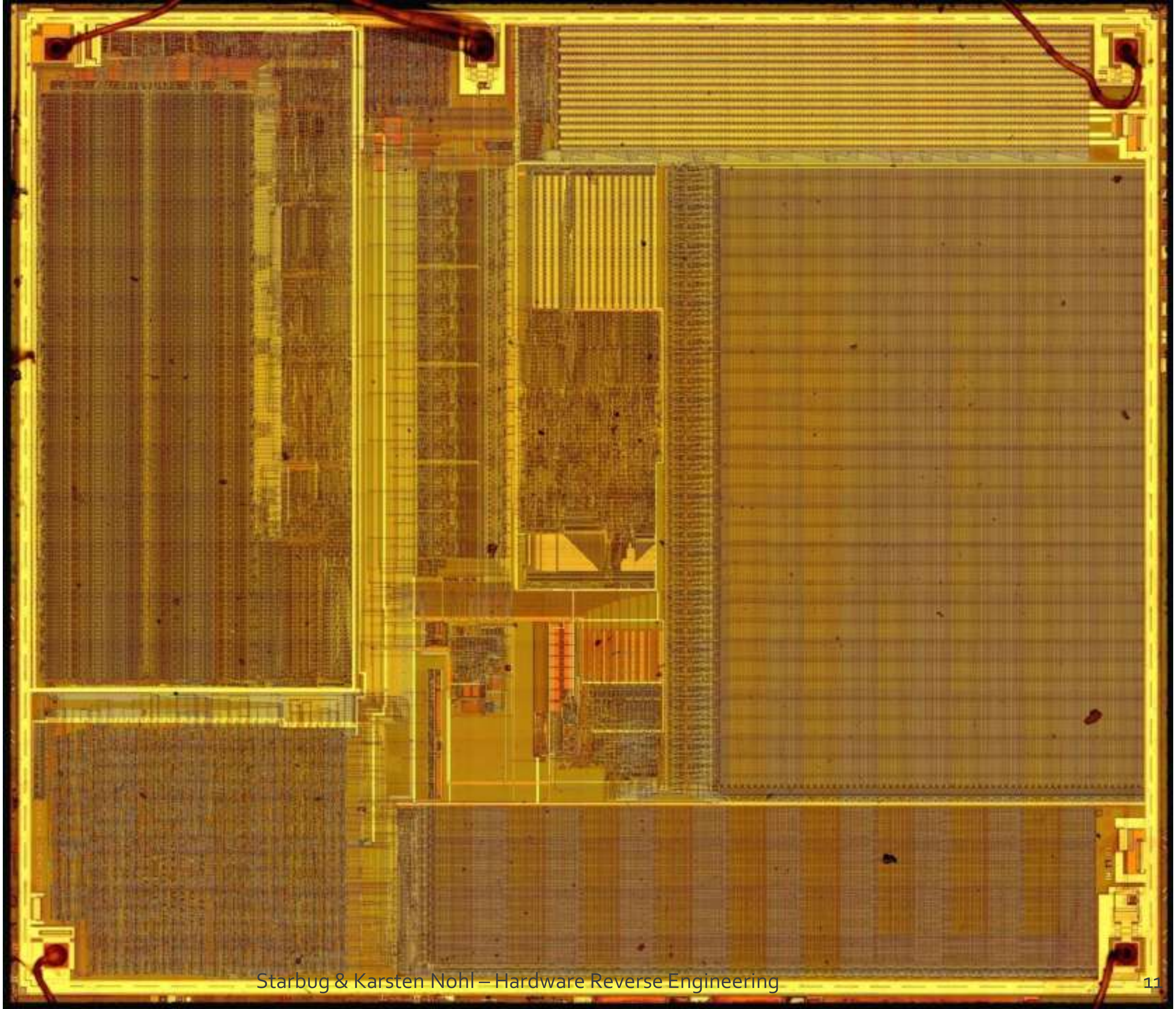


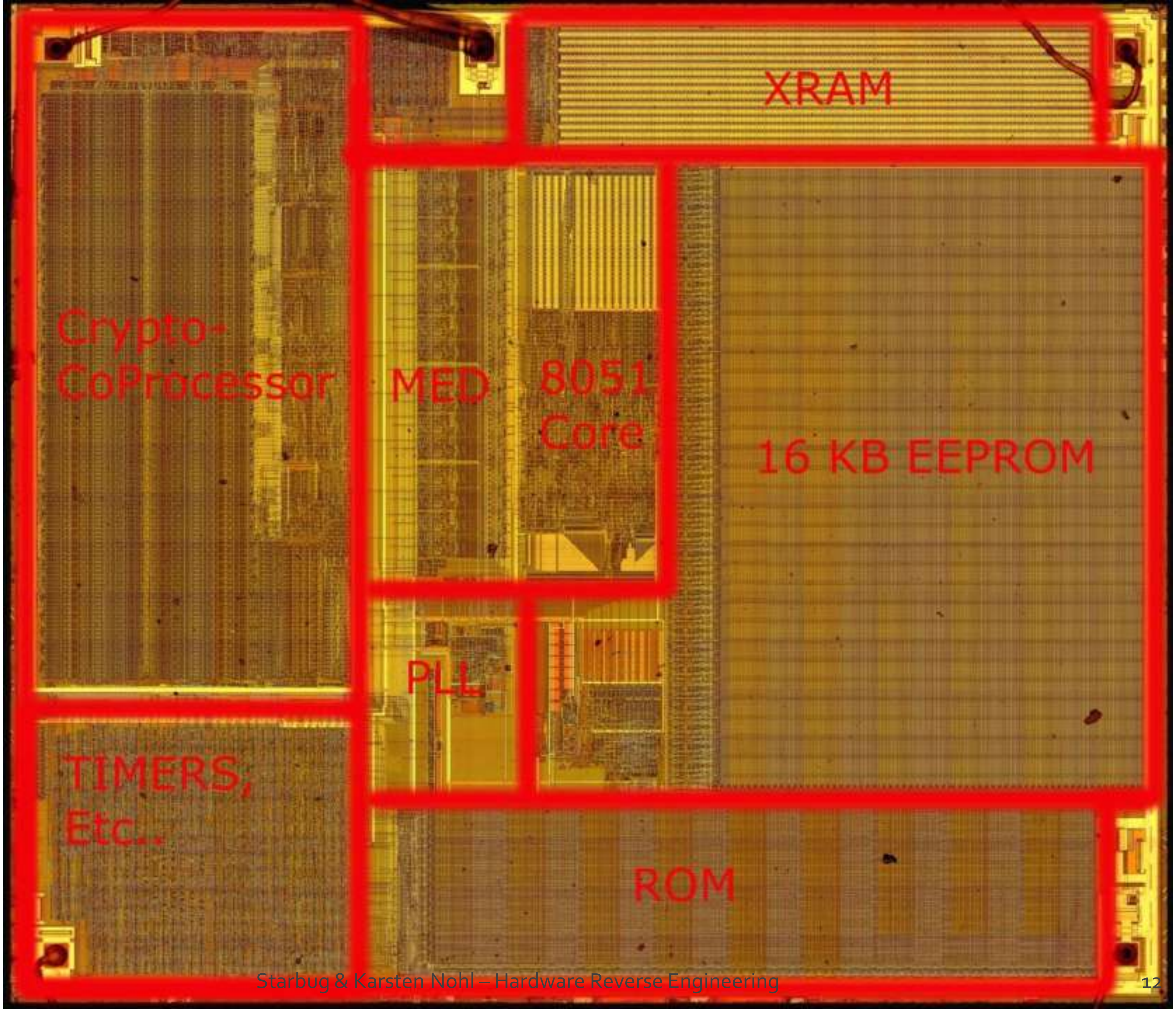


- Impact:
  - Find proprietary encryption
  - Open cryptographic key storage

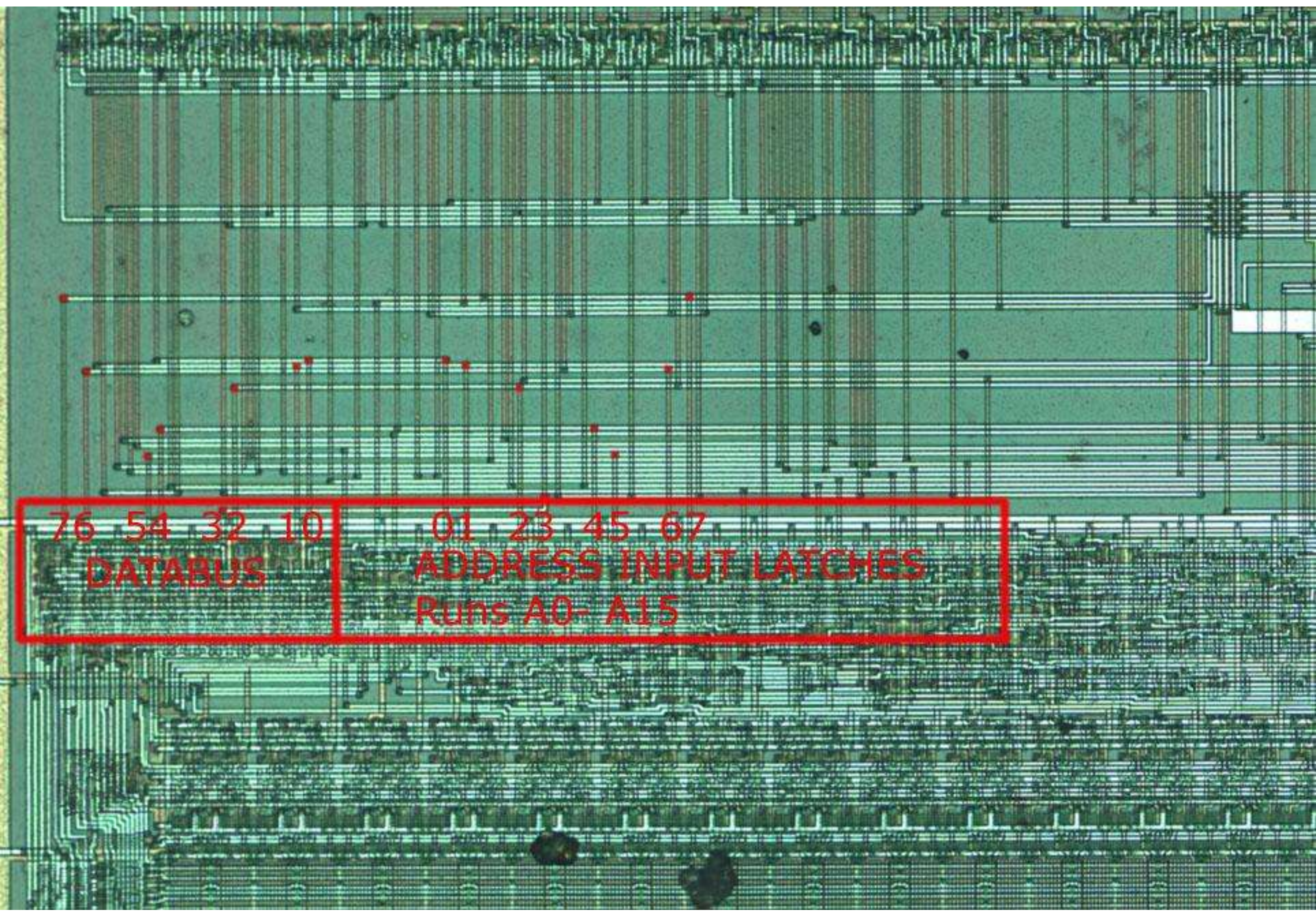
Microchip Basics

Infineon SLE66, courtesy Flylogic





Infineon SLE66, courtesy Flylogic

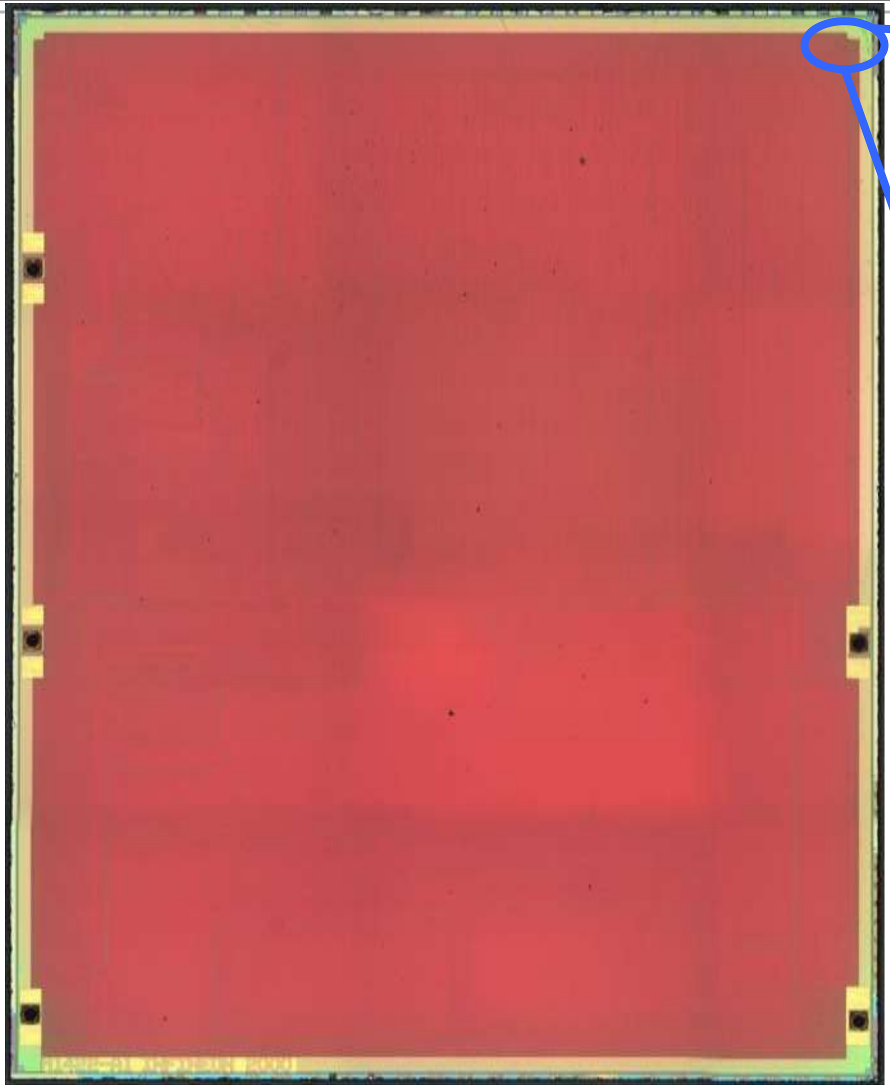


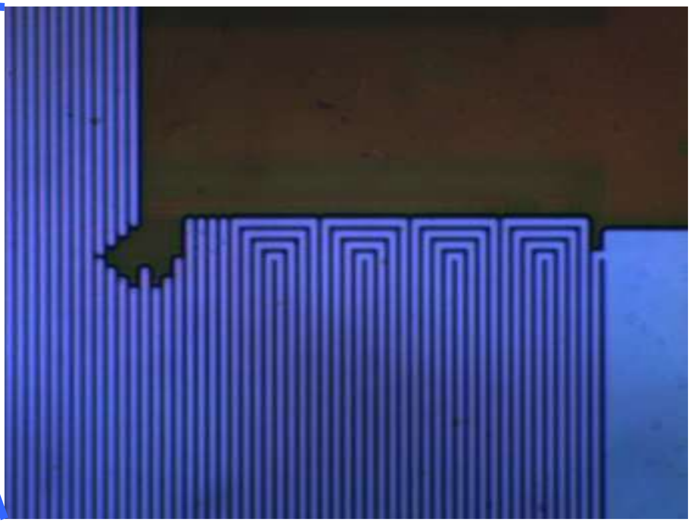
Infineon SLE66 address/data bus, courtesy Flylogic

Understanding Chip Layout

- Analyze chips using "last principles"
  - Principle #1: Chips are structured
    - Crucial for design partitioning and refactoring
  - Principle #2: Chips are designed to be read back
    - Enables prototyping and debugging
- Complement analysis with "first principle"
  - Principle #3: Nothing can be hidden in silicon
    - Chips are self-contained; hence all data, programs, and algorithms are available on the chip

Protection Meshes





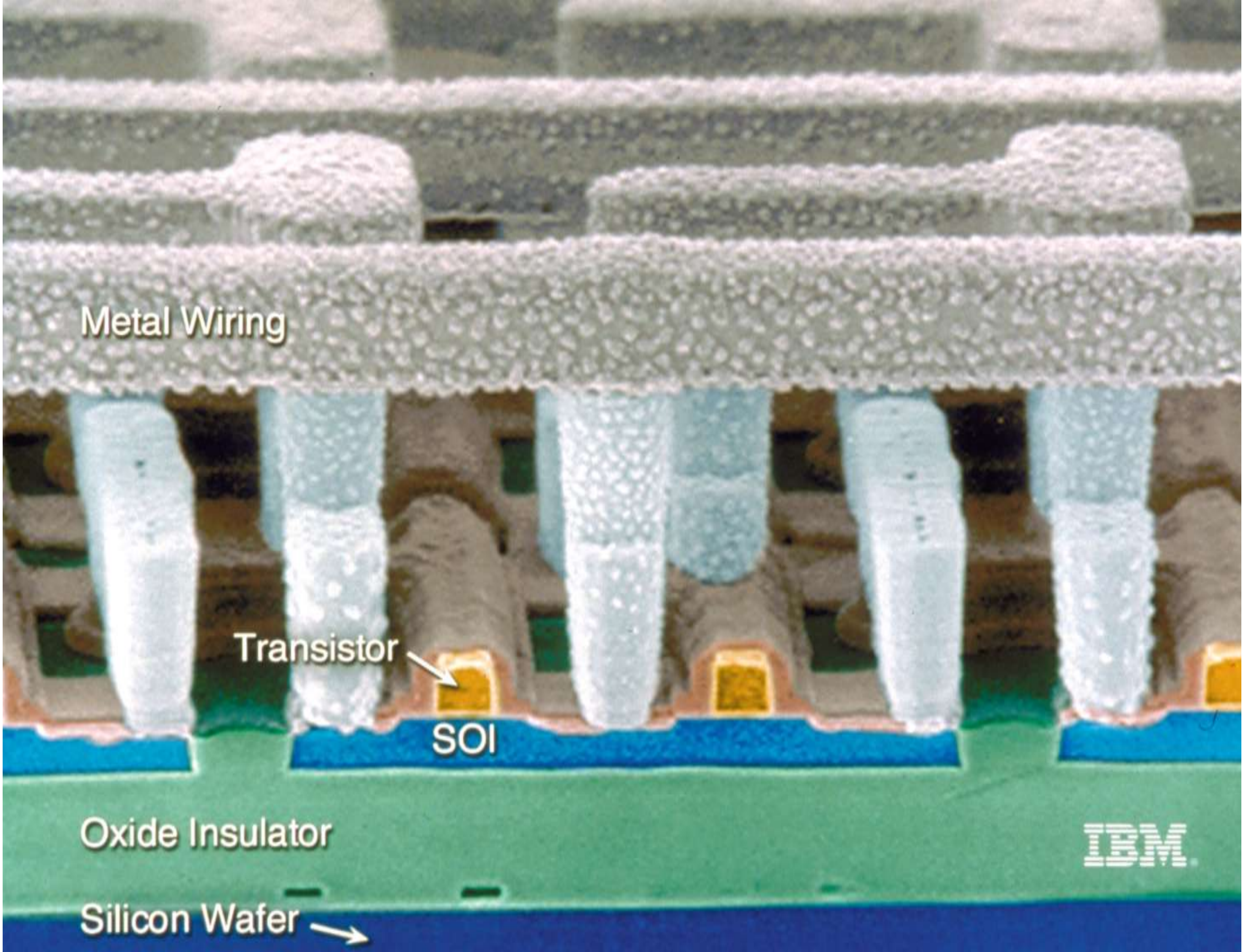
- Meshes can sometimes protect data, but not algorithms

"Last resort": Hide security in secret algorithms.

Reverse-Engineering Secret Algorithms

Obtaining Chips

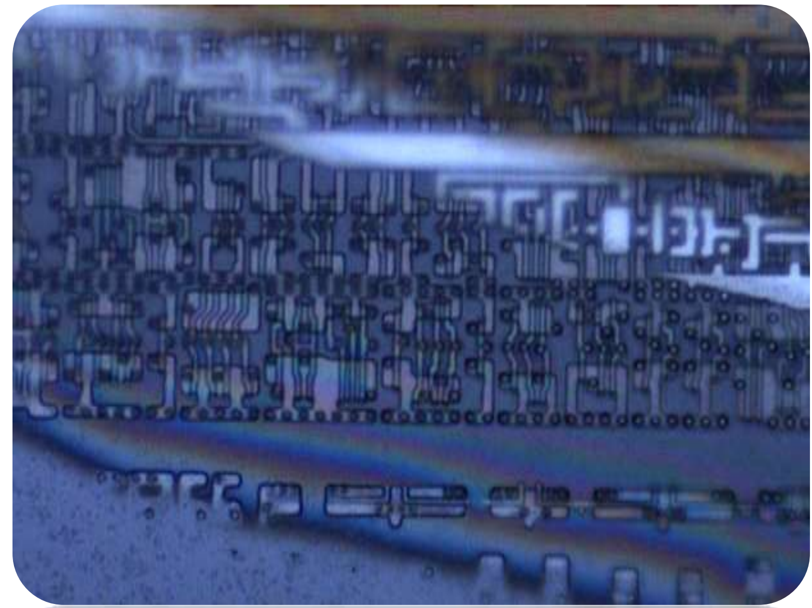
- Chemically extract chips:
  - Acetone
  - Fuming nitric acid


Metal Wiring
Transistor
SOI
Oxide Insulator
IBM
Silicon Wafer

Revealing Circuits

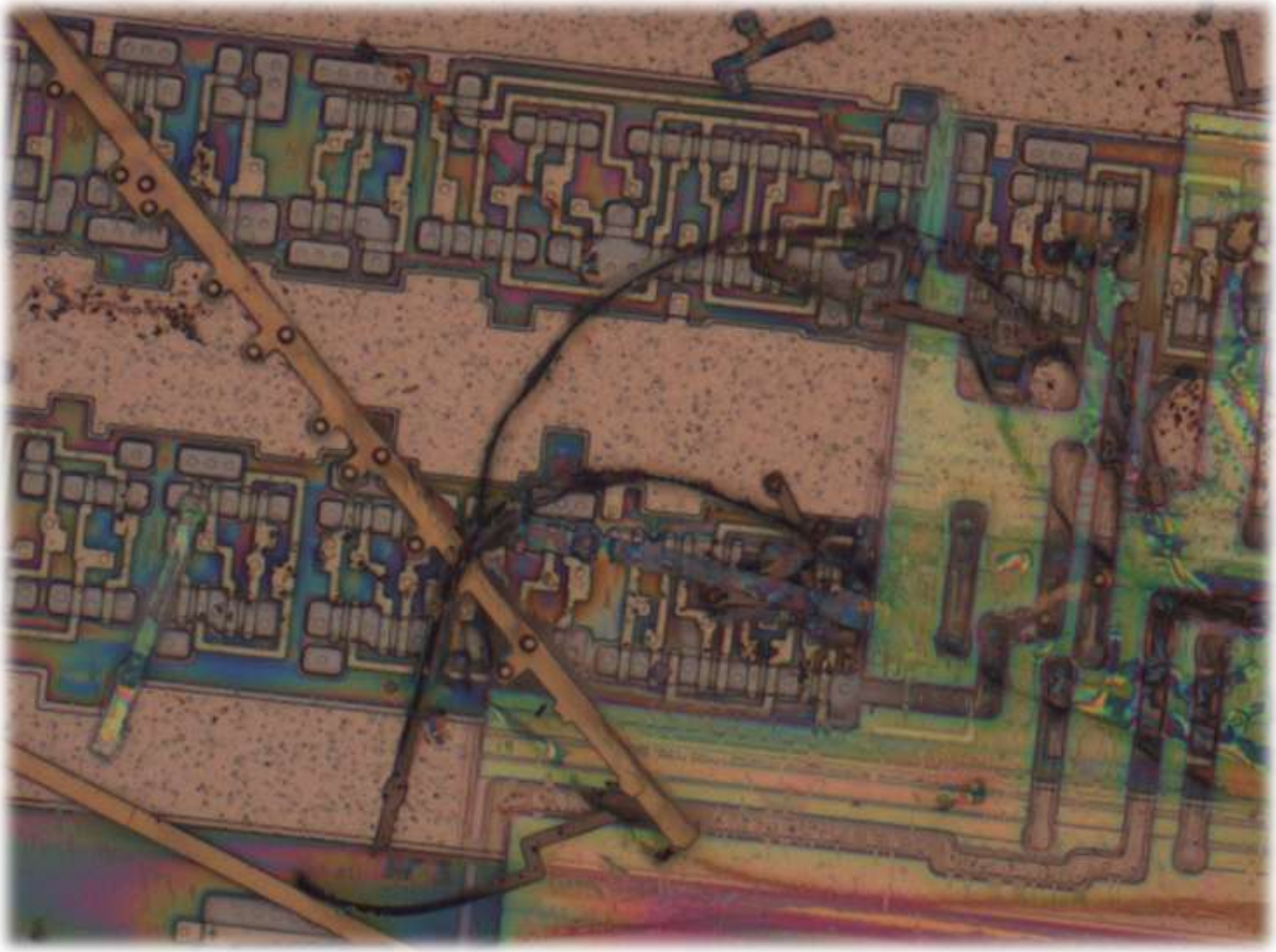
Polishing:

- Automated with machine
- Manually with sand paper



- Potential problem: tilt
- Solution: glue chip to block of plastic

Etching with HF (Hydrofluoric Acid)

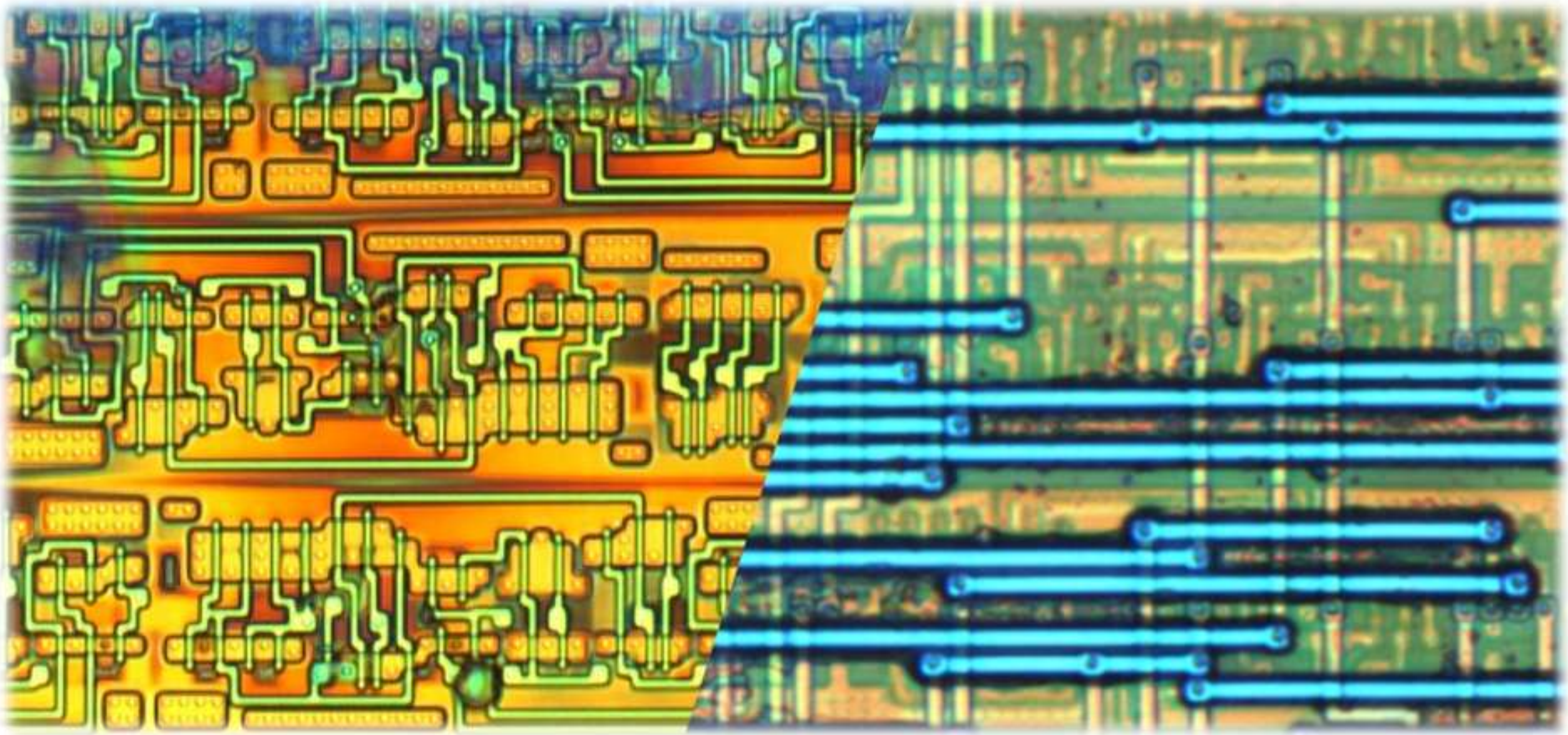


Imaging Chips

- Simple optical microscope
  - 500x magnification
  - Camera 1 Mpixel
  - Costs < $1000, found in most labs

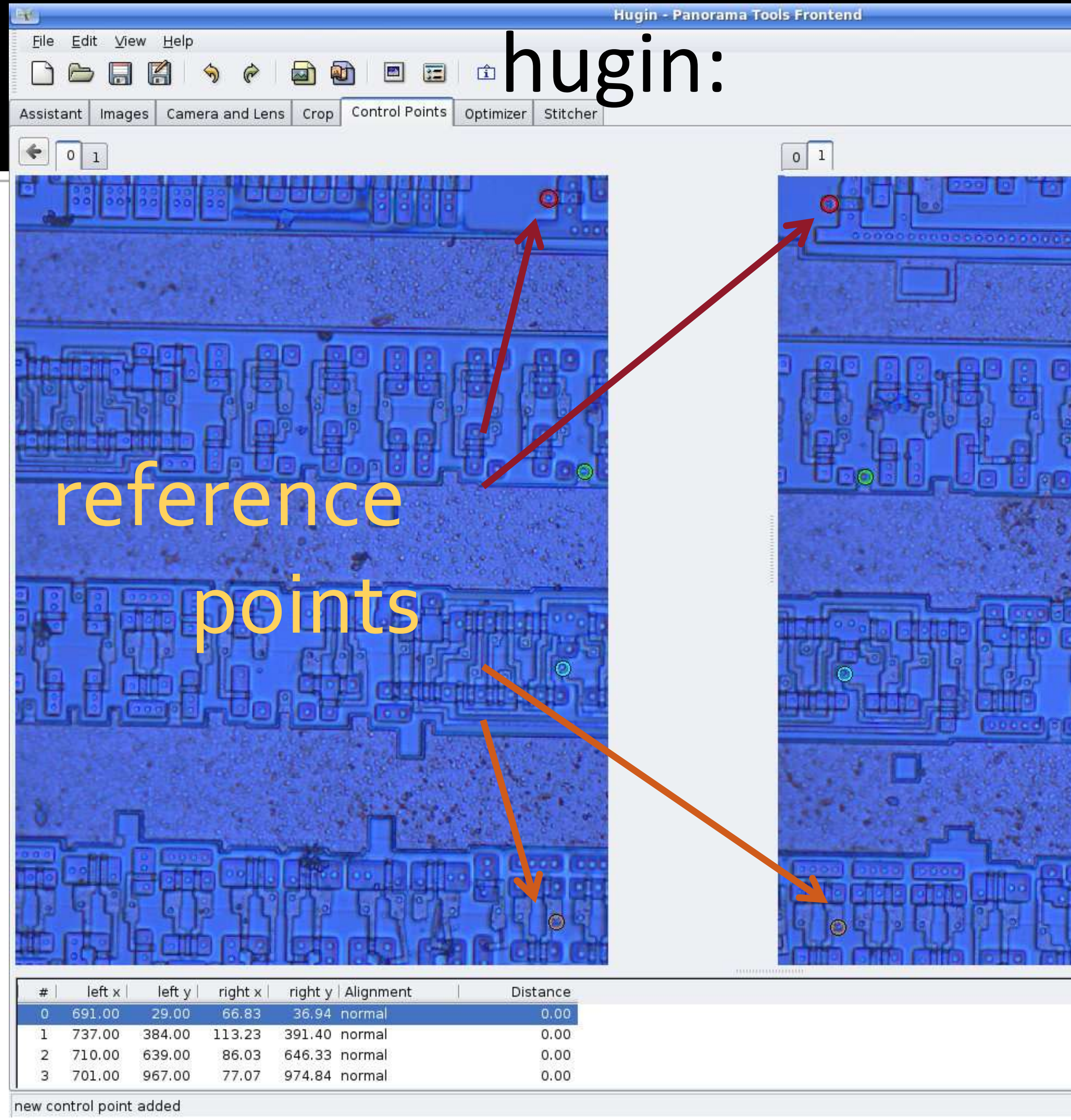
  — or—
- Confocal microscope
  - Colors images by layer
  - Makes structures easy to spot
  - Expensive: > $10k

Deluxe Imaging: Confocal Microscope

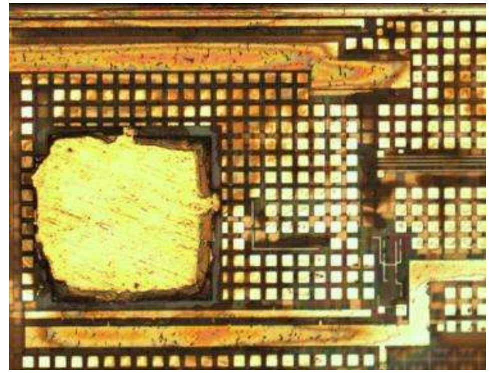


Stitching Images

- Need to stitch 100x100µm images
- Tool of choice: hugin
- Borrowed from panorama photography

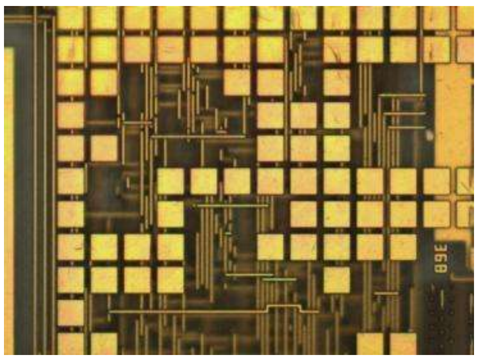


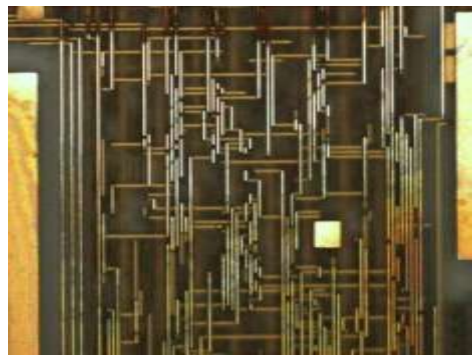
Chip Layers

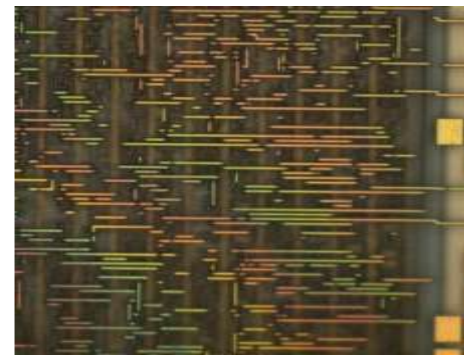


Cover layer (optional)

Interconnection layers



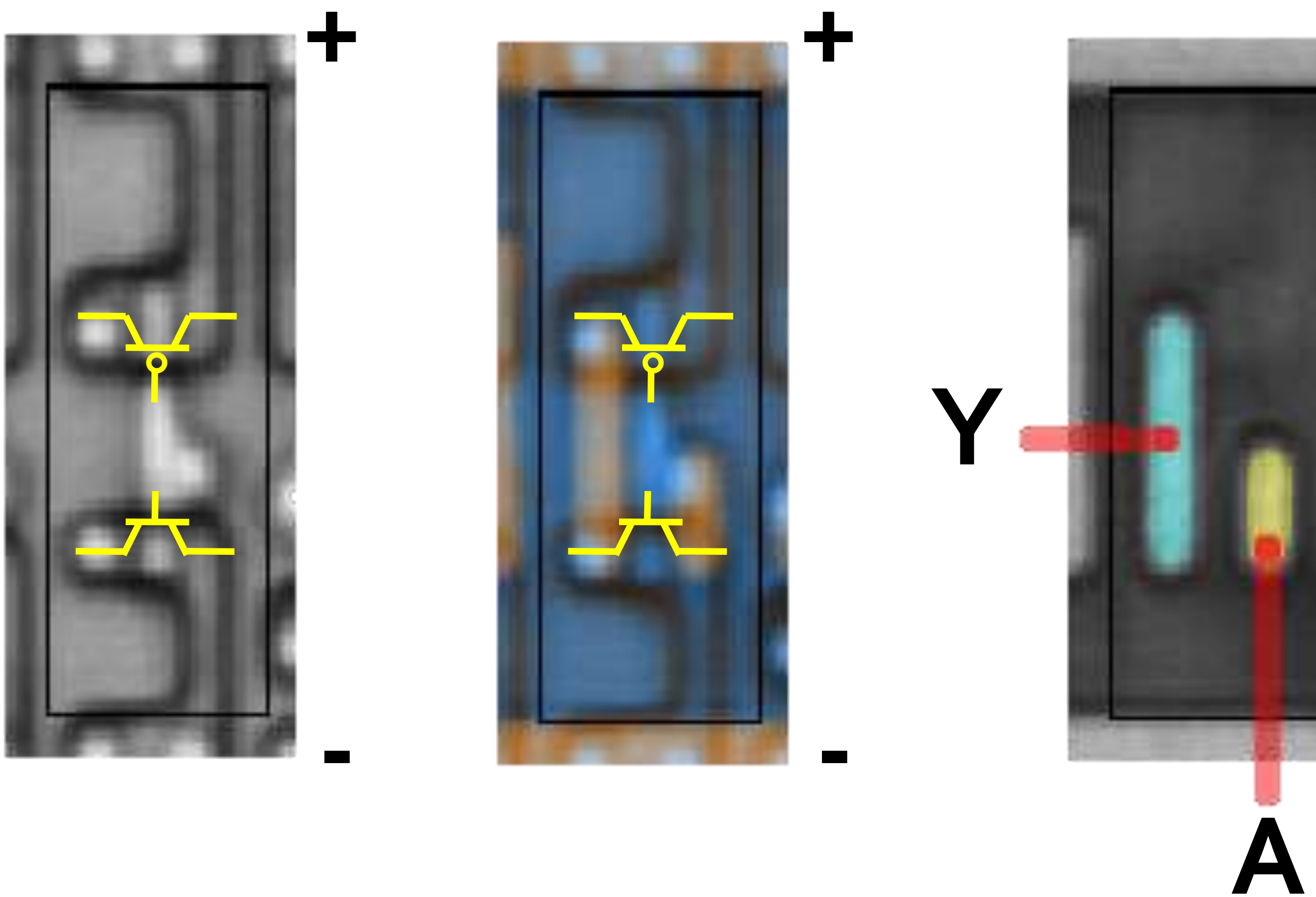




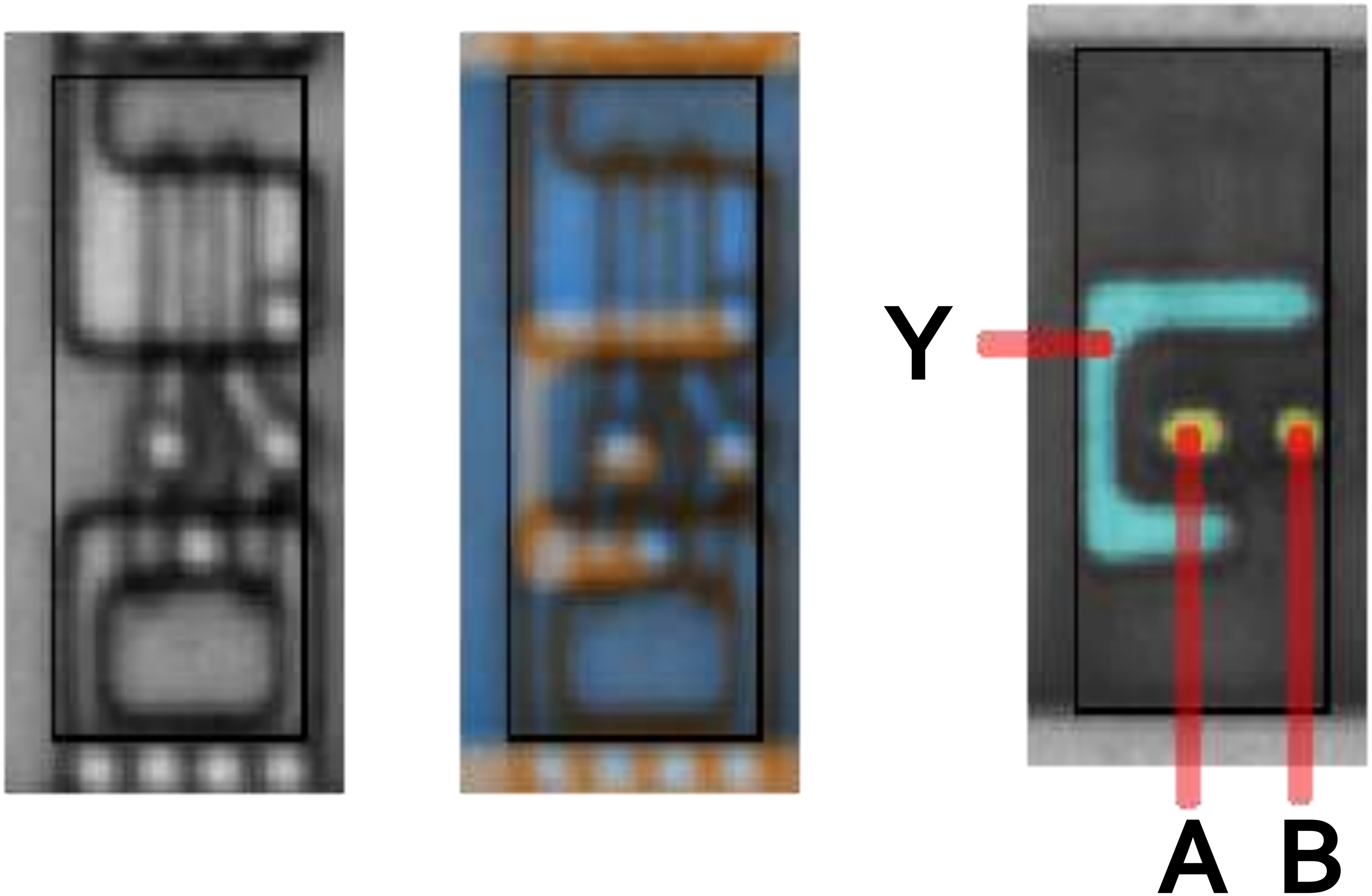
Logic layer

Transistor layer

Logic Gates – Inverter



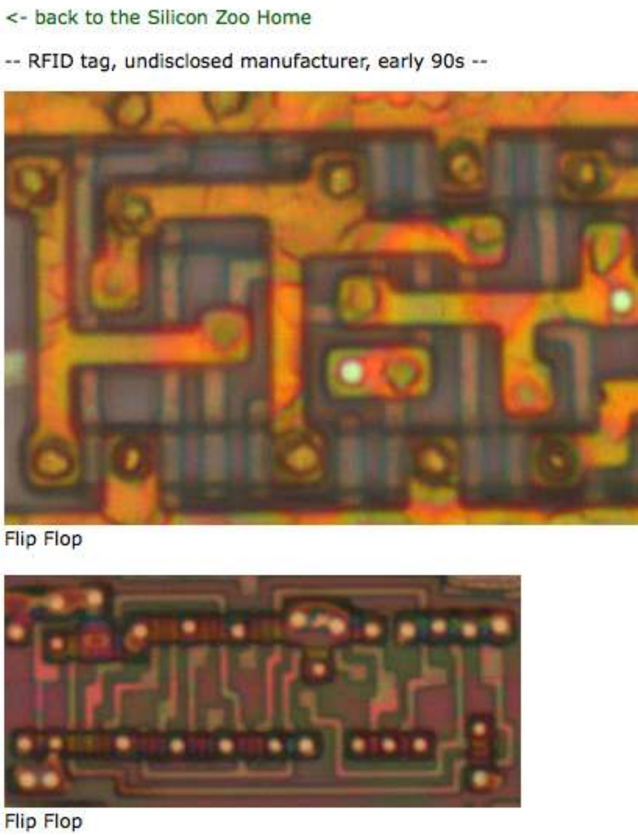
Logic Gates – 2NOR



The Silicon Zoo

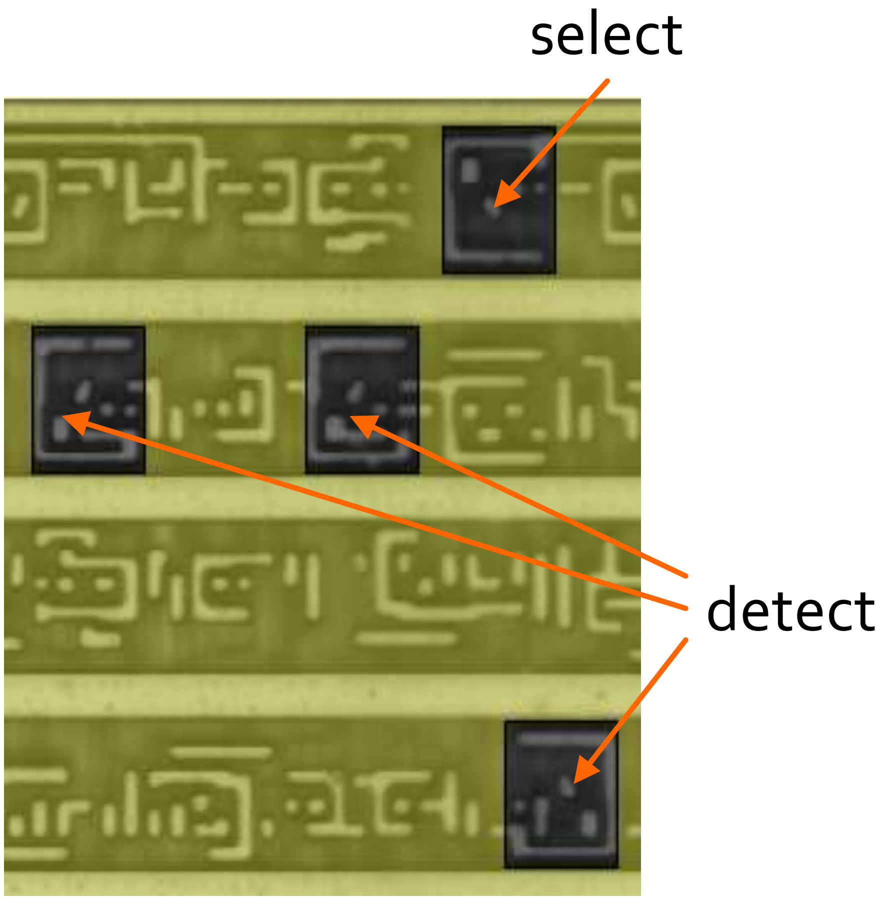
www.siliconzoo.org

- Collection of logic cells
- Free to everyone for study, comparison, and reverse-engineering of silicon chips
- Zoo wants to grow—send your chip images!

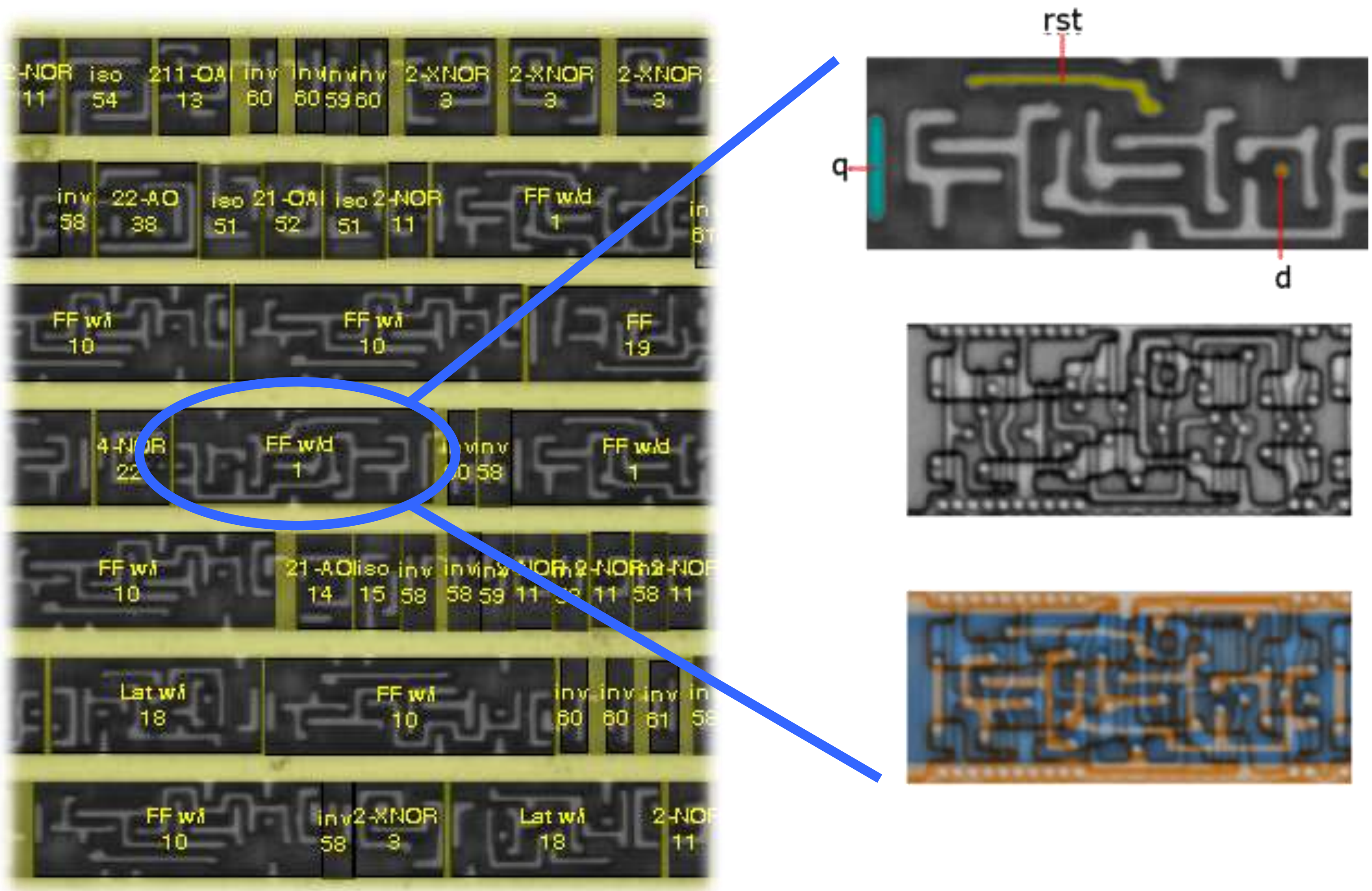


Standard Cell Library

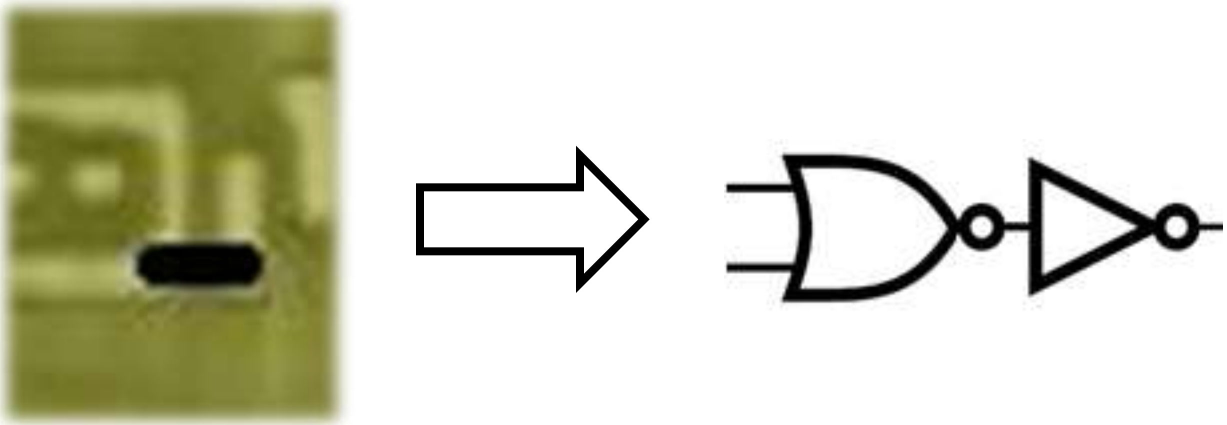
- Logic cells are picked form a library
  - Library contains fewer than 70 gate types
  - Detection automated (template matching using MATLAB)



Automated Cell Detection



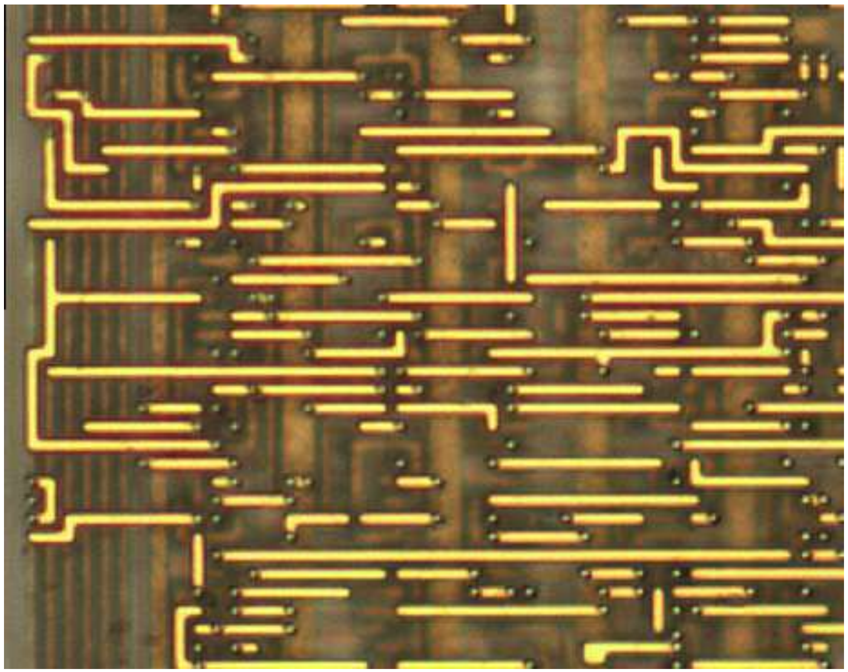
Logic Gates Interconnect

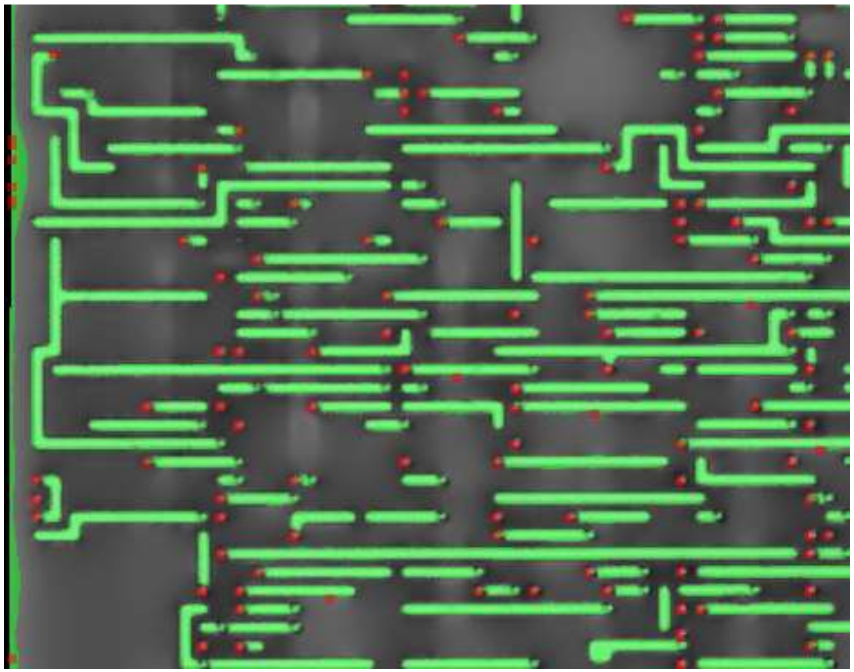


- Mifare: 1500 connections for Crypto-1
- DECT: 2000 connections for DSC
- Manually tracing connections
  - Tedious, time consuming
  - Error-prone (but errors easily spottable)
  - Tracing automated by now

Tracing Connections

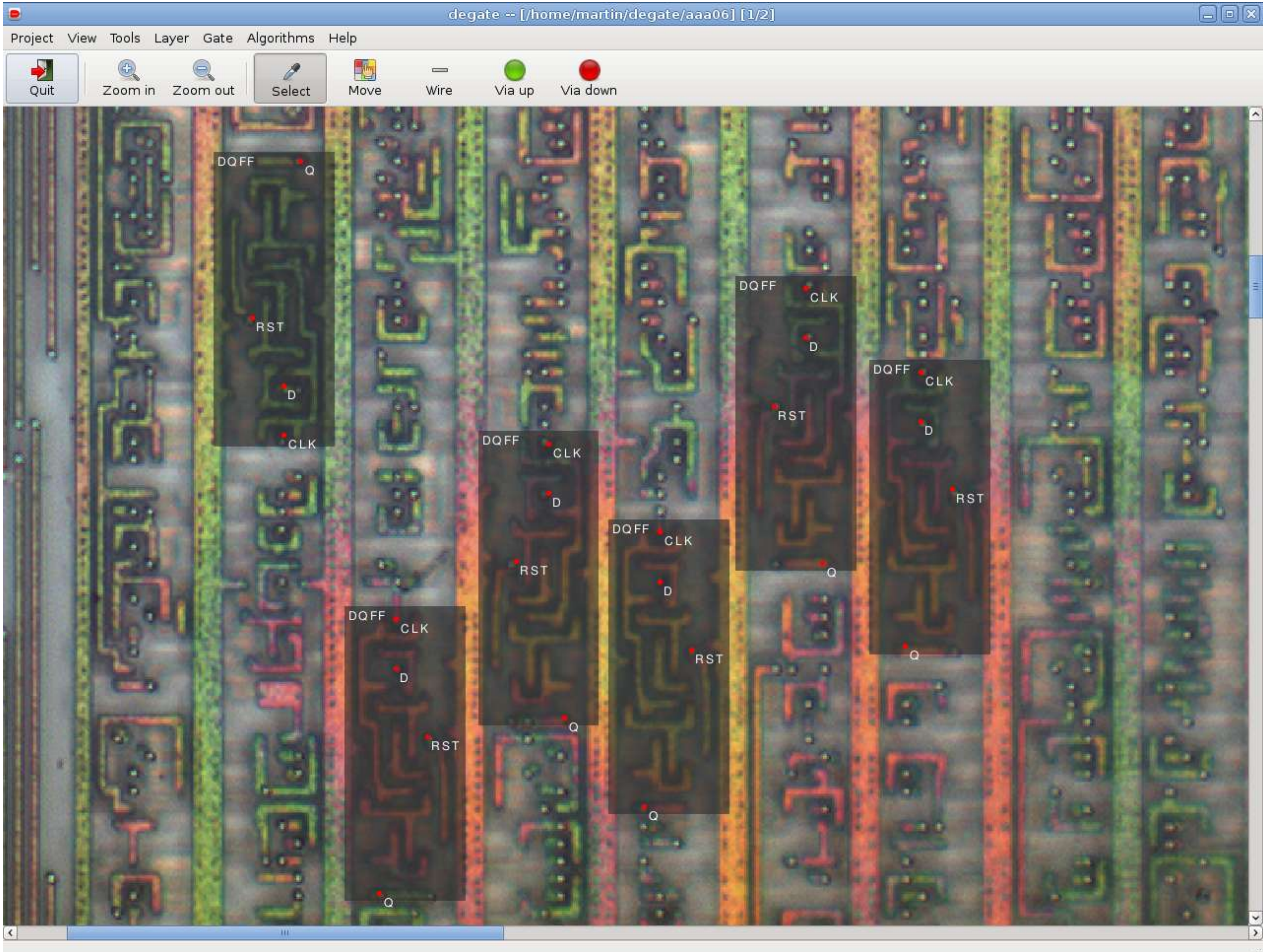
Automated Tracing





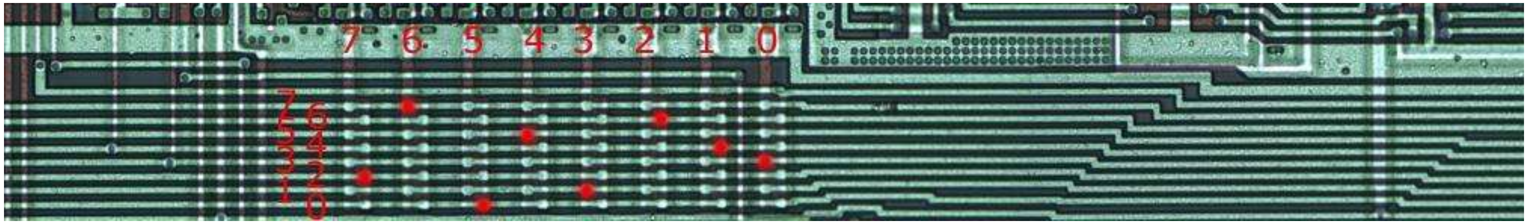
Metal wire

Intra-layer via


degate -- [/home/martin/degate/aaa06] [1/2]
Project View Tools Layer Gate Algorithms Help
Quit
Zoom in
Zoom out
Select
Move
Wire
Via up
Via down
DQFF
Q
RST
D
CLK

Countermeasures

- Obfuscated placing and wiring of logic cells
  - May defeat human inspection, but not automated tools



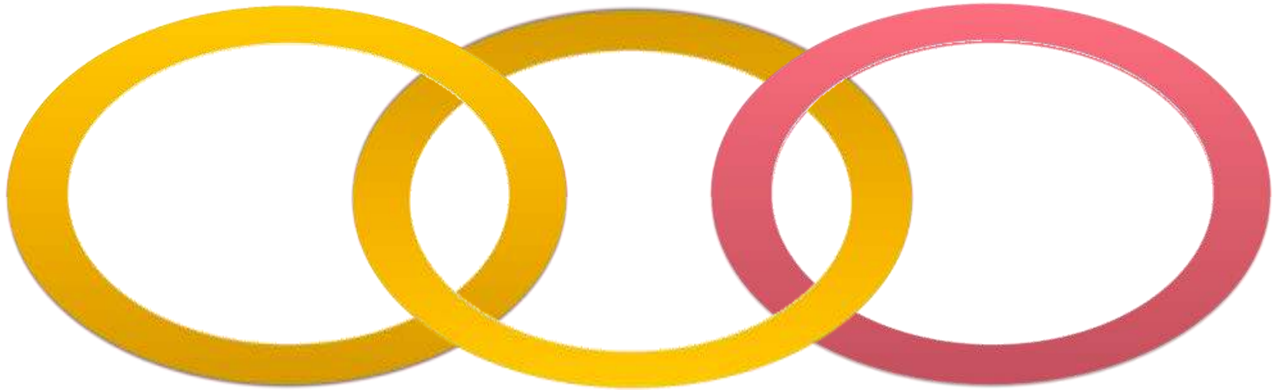
Source: flylogic.net

- Dummy cells
  - Makes reversing harder, but not impossible
- Large chips
  - Huge effort, huge rewards?
- Self-destructive chips?
  - May protect secret keys, not secret algorithms

Mifare Classic Break

- Mifare cards uses proprietary Crypto-1 algorithm
  - Never publicly reviewed for 20+ years
- We reverse-engineered algorithm and announce insecurities at 24C3
- Feb/Mar: Reports find Crypto-1 to be strong enough for a "few more years"
  - We releases more details about attacks
    - Final report recommends migration
- April: Dutch researchers publicly demonstrate attacks against Oyster
  - Law suit erupts, free speech prevails
  - Details published in October

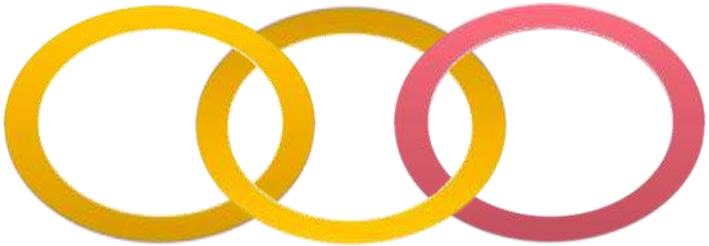
Outlook: Next Weaknesses



Security protocols | Cryptographic functions | Key storage

- Once strong cryptography is used, key storage becomes weakest link
  - More ubiquitous systems typically have more copies of the secret keys in accessible places

Key Storage



- Secret keys can be stored:
  - Online:
    - Keys only stored on central server
    - Expensive setup, long response times
  - Semi-online:
    - Devices receive keys at boot time
    - Keys often stored in DRAM at runtime; bad idea!
  - Offline:
    - Devices “securely” store key copy

Key Derivation

- Secret keys should be
  - Different for every user
    - Requires many different keys
  - Immediately accessible
    - Requires small number of keys

- Best practice: derive user keys from master key; store master key in „key vault“

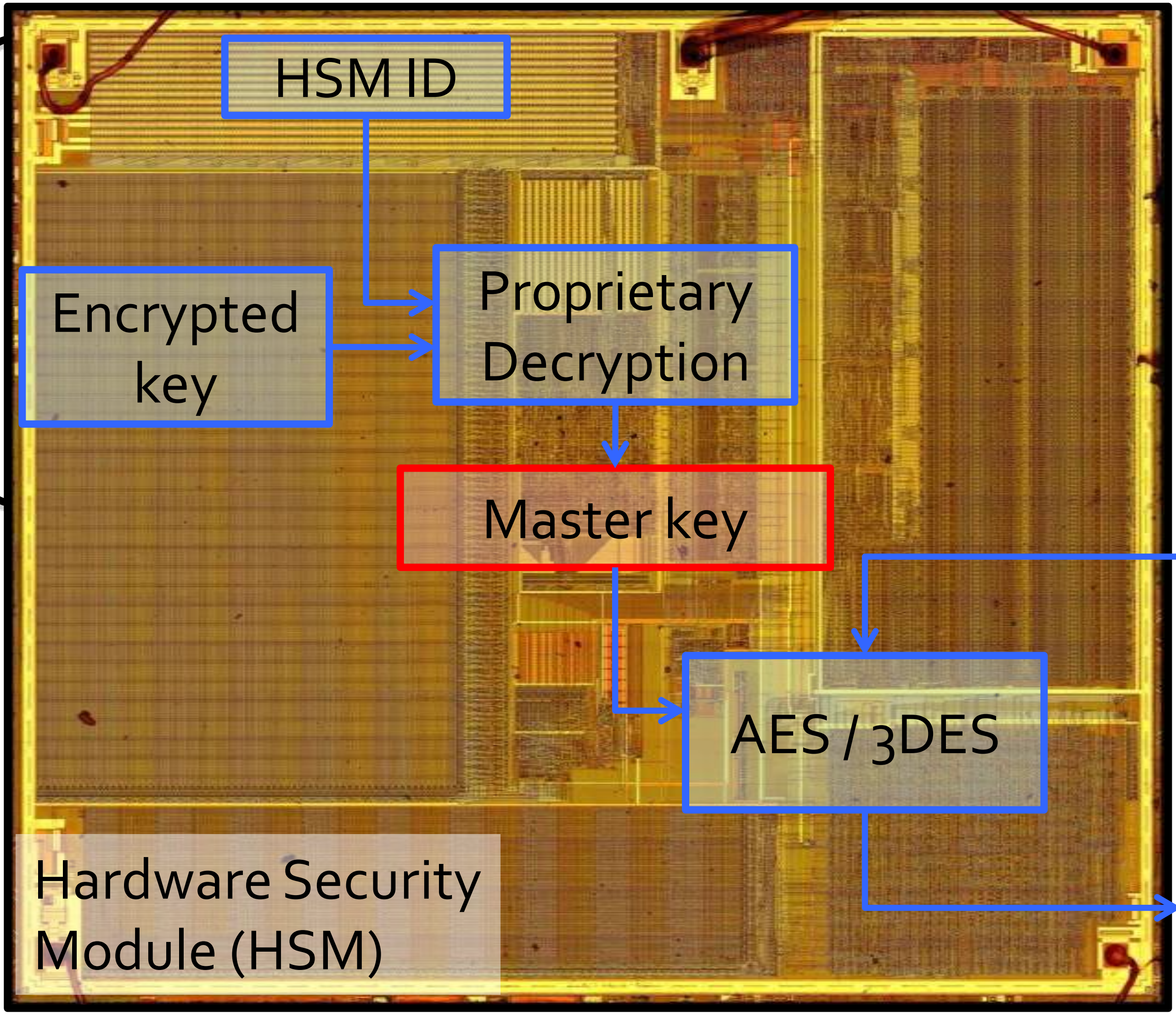
Secret Key Storage

- Hardware Security Modules (HSM)
  - Used in ATMs (cash machine), few smart card readers
  - Use proprietary encryption
  - Hence, can be broken
    - Usually high effort (> $100.000)
- Secure Access Modules (SAM) are much easier to break
  - Credit card / smart card readers

Key Vault

Everything needed to disclose key is found on chip

Finding secret algorithms might be costly

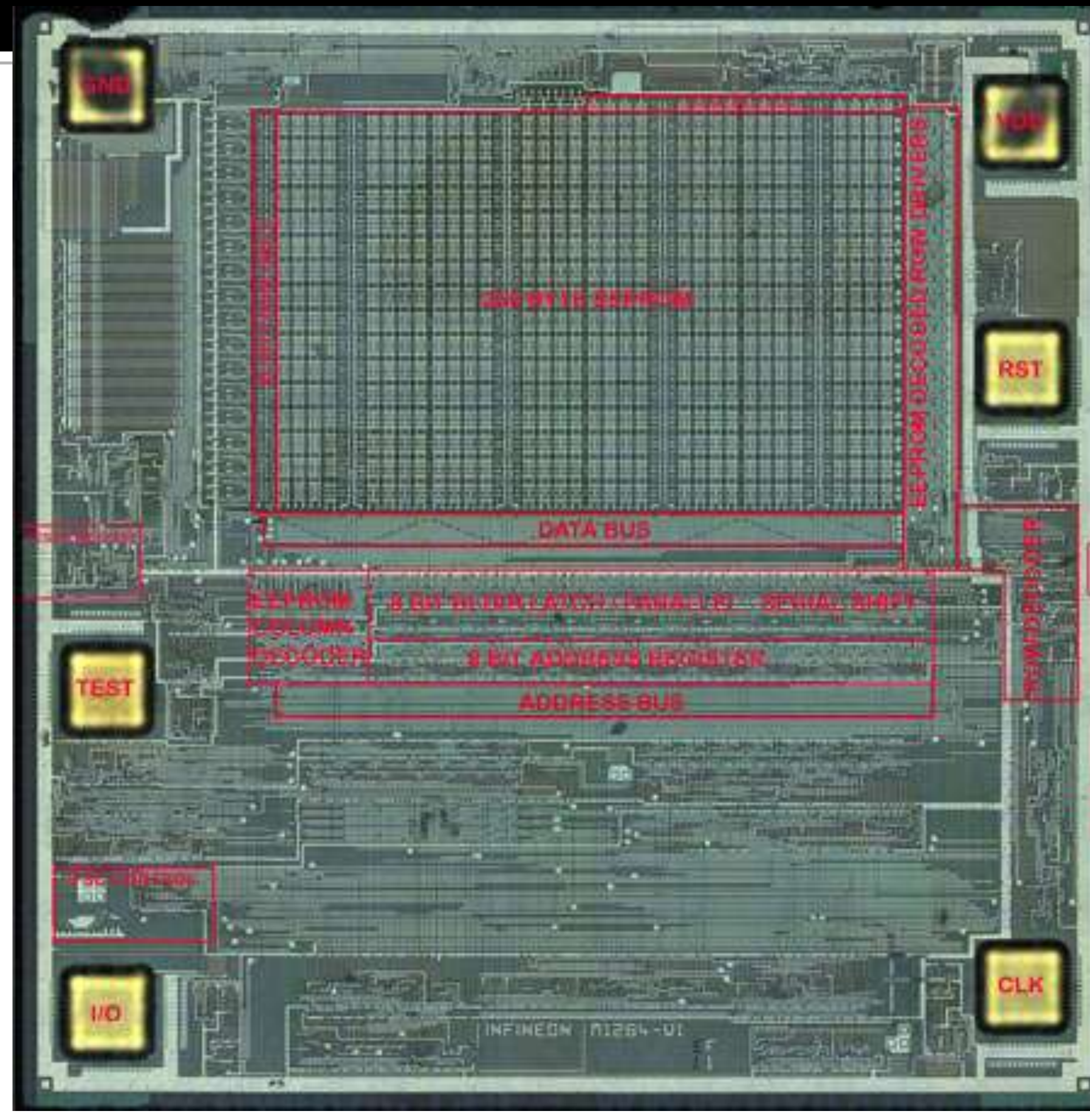


Card ID, sector, …

Card key

SAM chips

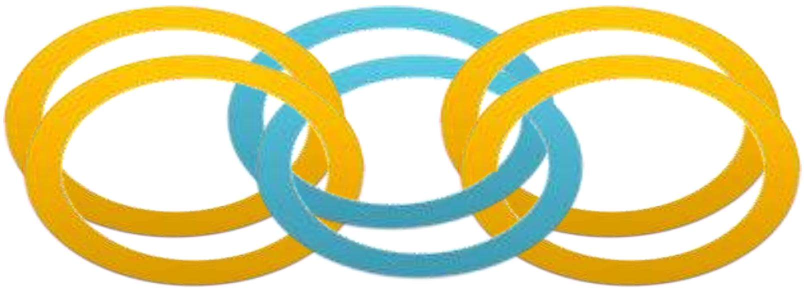
- „Secure" Access Modules are standard micro-processors
  - Low effort to extract master keys
  - SIMs/SAMs are becoming cheaper and less secure!
  - (cell phones are not any better)



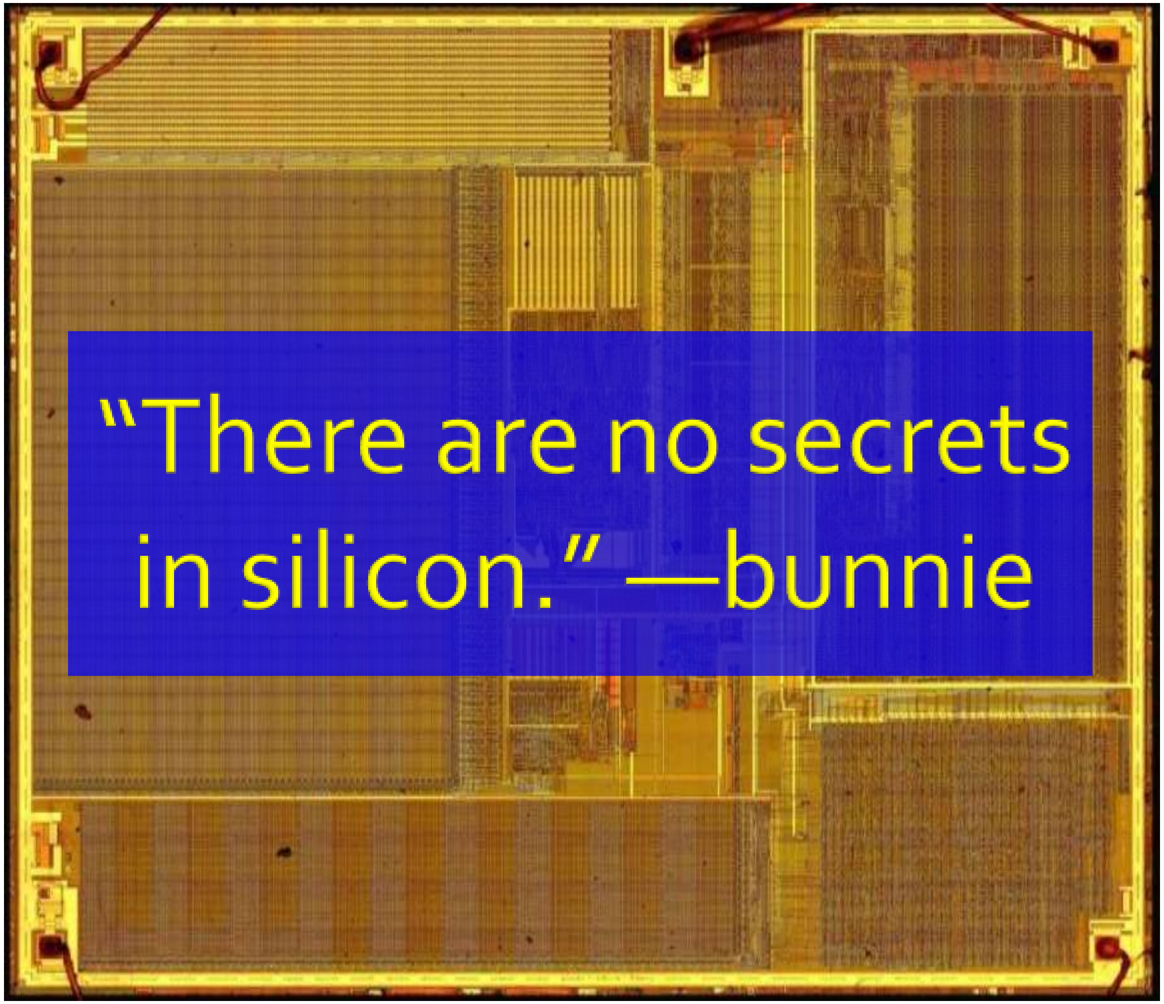
Source: *Flylogic*

Best-Practice Security

- Guidelines learned from past hacks include:
  - Prepare for security breaks, no measure is perfect
    - Need: redundancy, “layering”
    - Need: migration plan
  - Use standardized security
    - Never rely on your own security “inventions”
  - Manage risks through threat modeling
    - Find acceptable balance between potential losses and cost of security



Questions?



Karsten Nohl
nohl@virginia.edu
Starbug
starbug@ccc.de