Degate

The stakes and challenges of silicon reverse engineering

https://www.degate.org

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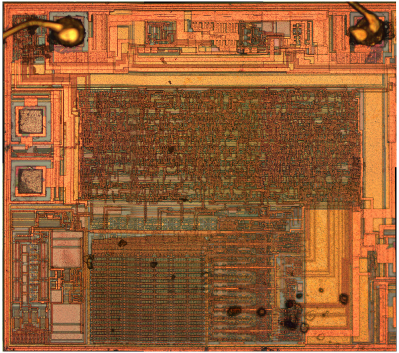
Degate Community,
2024

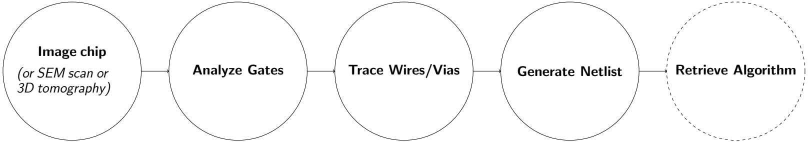
What is Silicon Chips RE?



Same idea than with software RE (from binary, to assembly and to code), silicon chip RE go **from silicon**, **to images**, **to transistors**, **to gates**, **to netlist** and **to algorithm**.

With proper preparation and knowledge, we can go into silicon, **analyze transistors**, **retrieve gates/wires/vias** and **reconstruct implemented algorithms**. This can be used to **analyze old hardware**, build **software emulators**, search for **vulnerabilities** and **backdoors**, **break/test a protection**, **secret extraction** or **check intellectual property**.

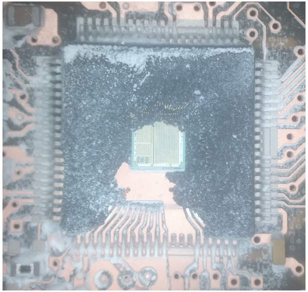
Used in IC industry for **fault/failure detection** & analysis, but **not at the same scale**.



How to Access Silicon?

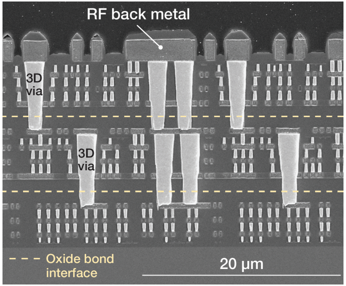
Can be very costly (plasma & laser) and destructive... But also accessible with simpler methods (like chemical/mechanical). More on [4].

1. **Decapsulation** (heat, acid, mechanical, plasma, laser...)
2. **Delayering** (chemical, abrasive, laser, plasma...)
3. **Cleaning** (ultrasound, acid...)



[1]

[2]

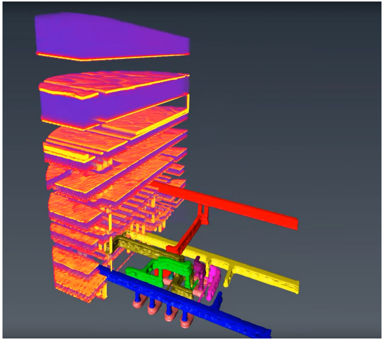


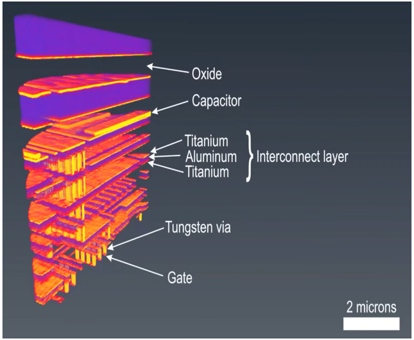
MIT

How to Retrieve Images?

Using each layer (invasive) or directly using the chip (non-invasive):

- Take very-high resolution images from **optical microscope** (basic, confocal) ;
- Scan from an **electron microscope** (SEM, TEM...) ;
- Generate a 3D model using **electron tomography** ;



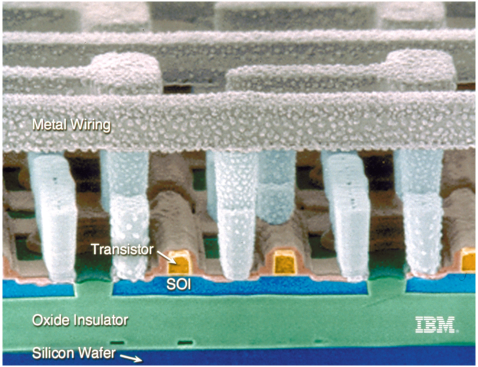


[1]

How to Perform the Analysis?

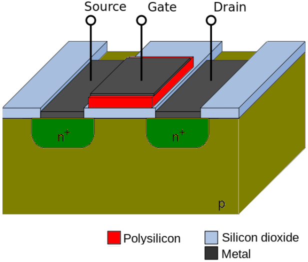
Overview:

1. Choose a **zone of interest**,
2. Identify each **gate type**, annotate, and place in a **"gate library"**,
3. Find other **gates instance** from gate library,
4. Link gates by tracing **wires and vias**,
5. Export to **netlist** (e.g. by translating each gate to VHDL/Verilog code).

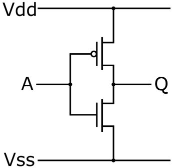


How to identify a transistor?

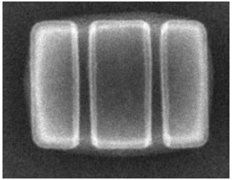
1. Search, at transistor layer, for **doped zones**.
2. Spot the **zebras**.
3. Use logic to identify the **type of each transistor** (e.g. PMOS are bigger to compensate with lower hole mobility).
4. Search for **wires** (to identify inputs and outputs).



(NMOS, *Wikipedia*)

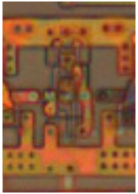


(Inverter, *Wikipedia*)

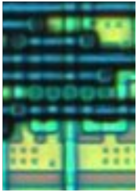

(PMOS [10])

How to Identify a Gate?

Transistor layer

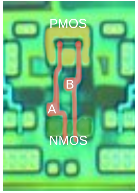


Logic layer

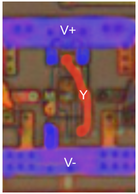


Metal layer

⇓

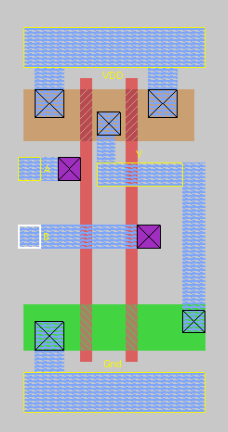


P & N zones and 2 inputs



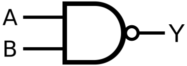
V+ & V-, and output

⇒



[7] ⇒

NAND gate!



A	B	Y
0	0	1
1	0	1
0	1	1
1	1	0

How to Retrieve the Netlist from Analyzed Gates?

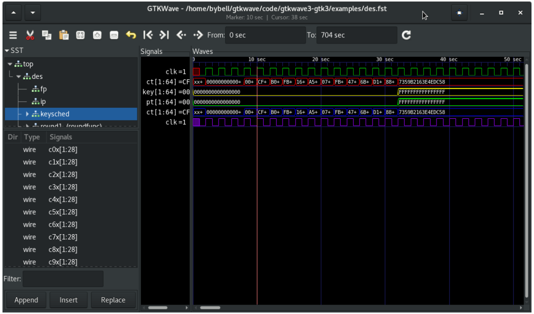
```
module jsrflipflop(q,qbar,clk,rst,sr);
    output reg q;
    output qbar;
    input clk, rst;
    input [1:0] sr;

    assign qbar = ~q;

    always @(posedge clk)
    begin
        if (rst)
            q <= 0;
        else
            case(sr)
                2'b00: q <= q;
                2'b01: q <= 0;
                2'b10: q <= 1;
                2'b11: q <= 1'bx;
            endcase
    end
endmodule
```

- Each gate can be described with **hardware description language (HDL)**, like **Verilog** or **VHDL**.
- **Wires & vias** can also be described.
- That's all we need to **obtain the netlist**!

We can, from HDL, **simulate the extracted netlist** and **find incoherence** (*example with gtkwave below*):



How to Get the Algorithm/Specification from Netlist? [3]

After retrieving the **netlist**, we are left with a **huge and "unorganized" number of gates**. The **specification discovery** phase aims to **retrieve IC's algorithm/functionality** from the extracted netlist.

Using specific algorithms you can **automate some phase**:

- **Partitioning** of the netlist (*to retrieve a semblance of "code" structure*).
- **Recovery** of the registers (*if applicable*).
- **Identification** of the extracted "groups" (*partitions*) of the netlist.
- **Construction** of a library of netlist components from the identified "groups".

These algorithms **need to allow some degrees of error** from the netlist extraction. This phase is ∼analogous with **duplicated, standard & library functions identification** for **software engineering**. A nice open source tool for this is **HAL**[1] (compatible with Degate's outputs!).

[1] https://github.com/emsec/hal

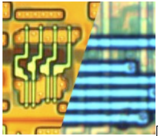
To Summarize

Image chip *(or SEM or 3D tomography)* → **Analyze Gates** → **Trace Wires/Vias** → **Generate Netlist** → **Retrieve Algorithm**

Image chip
- **Decapsulate**,
- Select **area of interest**,
- **Delayer**,
- Clean,
- Stitch.


[2]

Analyze Gates
- Analyze transistors,
- **Identify each type of gates**,
- Retrieve all instances of each gate (**pattern matching**).


[2]

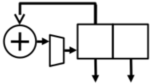
Trace Wires/Vias
- Identify **wires**,
- Identify **vias**,
- **Connect gates**.


[2]

Generate Netlist
- **Export netlist**,
- Gate simulation,
- Try to identify errors.

```
<?xml version="1.0"
<gate-library>
 <gate description=
  <ports>
   <port id="0" nam
   <port id="1" nam
```
[2]

Retrieve Algorithm
- Extract algorithm,
- **Discover specification**,
- Perform functional analysis[3],
- Build a **software emulator**,
- Try to **identify errors**.


[2]

Cost Perspective (1/2)

Costly solutions will give best results, and sometime reduce the difficulty for analysis software:

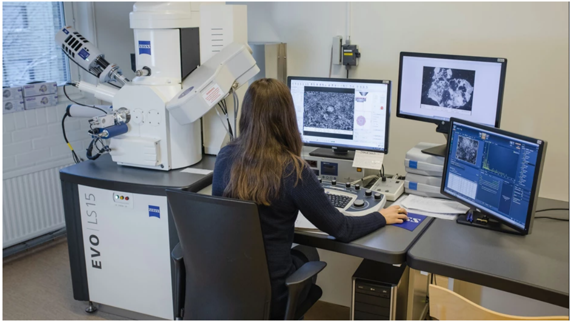
- **Decapsulation/delayering:** plasma, laser, FIB ;
- **Imaging:** Scanning Electron Microscope (SEM), other electron microscope (TEM, STEM, LEEM, PEEM...) ;
- **3D modelization:** electron tomography (3D) ;

Simpler methods rely on **mechanical & chemical** decapsulation/delayering and **optical microscopes** to obtain **very-high resolution but imperfect images**. Using images is more challenging: **color channels**, **impurity/damage/dust**, **single dimension**, **stitching**, **resolution**, **laborious work**...

Cost Perspective (2/2)

Chip samples cost are also to consider (when doing invasive analysis, you'll maybe need multiple samples of the chip).

Compared to software reverse engineering, there is a **lot more costs associated**, and a **higher entry barrier**.



A **new SEM microscope** can cost from **70k$ to over 1M$**. **Used instruments** can cost from **2,5k$ to 550k$**. Resolution may vary a lot.

And that's **just for imaging**!

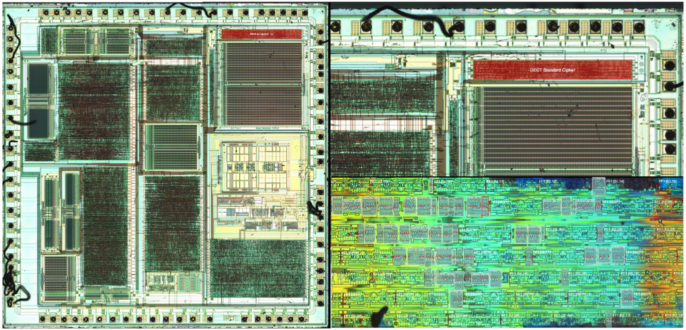
(Umeå University)

Analysis Perspective

- Newest chips **have ∼3nm transistors** and **billions of them**!
- Need automatic **gate recognition, wire tracing and netlist reconstruction**, which a human can't handle alone.
- Resulting images can be **millions of pixels large** (*width* > million pixels)!
- How to perform **template matching/image recognition** on such **gigantic images**?
- How to handle **all possible formats** (images, multi-layered images, SEM images, 3D tomography...)?
- There are so **many steps where that can go wrong**, or a **small error slips** into the analysis...
- Non-planerized IC exists (non repeated standard cells)!
- And what about **obfuscation**?

Human Perspective

- Need a **highly technical level** in several disciplines, this will help for **error spotting**, choosing a **zone of interest** and more.
- Need to **understand "silicon"** (how IC are made) and have **low-level electronic knowledge**.
- Have the necessary **equipment available**.
- Be **persistent** and **patient**.
- **Practice**.
- And **Have time!**



Importance for Cybersecurity

How can we **trust software** if we **can't trust hardware** (e.g. "specialized" ASIC)?

- Is there any **vulnerability in the hardware implementation** of an algorithm (e.g. crypto standard with predictable initialization, bad randomness...)?
- Is there any **hardware Trojan** (e.g. placed by the foundry)?
- If there is a vulnerability/backdoor, **patching is impossible**, far **more impactful** than software vulnerabilities.

Some examples of vulnerabilities found thanks to silicon RE:

- *Legic Prime*, *NXP Hitag2*, *DECT DSC*, *CryptoRF*, *Atmel CryptoMemory* & *NXP Mifare Crypto-1* (∼2008, Nohl et al): **weak (or potentially weak) cryptographic ciphers**.
- Undisclosed ones?

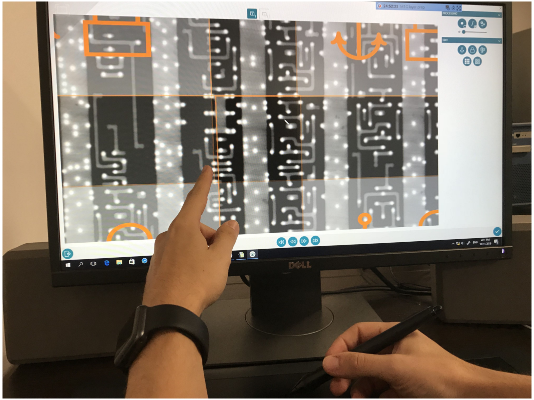
Available Tools & Products

Commercial products:

- **CHIPJUICE**: Extracting Data from Highly Encrypted ICs.
- *Internal tools*: for sure, there is a lot of them.

Open Source tools:

- **Degate**
- **psxrev**: SONY PlayStation PCB/chips reverse engineering.
- **Deroute**: Tool for untangling wires.
- **dietools**: Series of tools for die shot reverse-engineering.

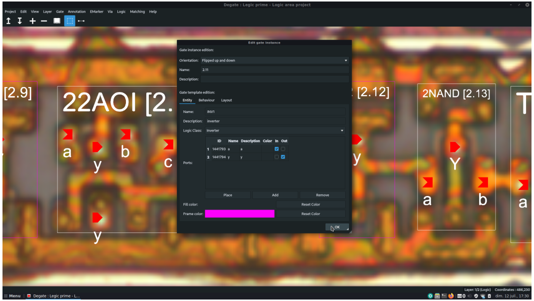


(Texplained)

Introduction

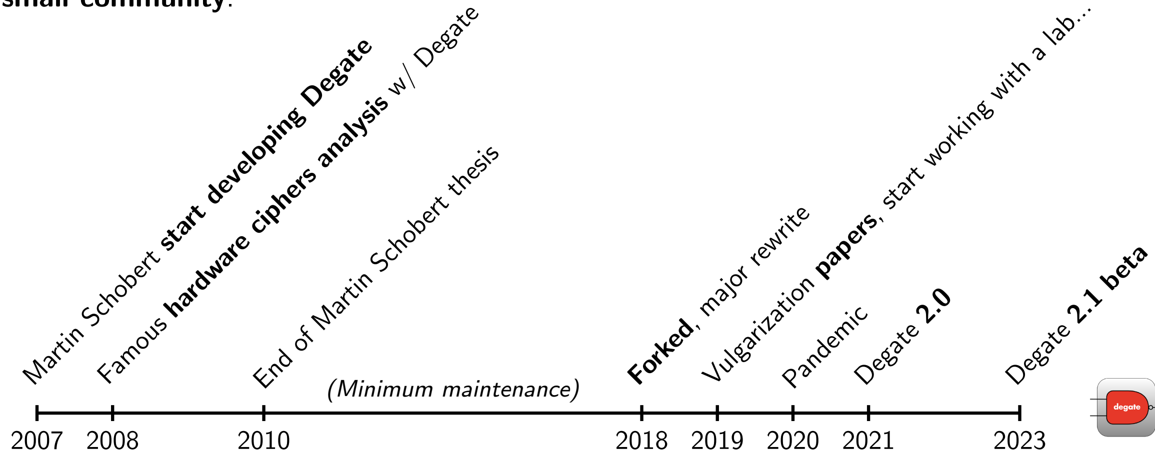
Degate is a multi-platform software for semi-automatic **Very-Large-Scale Integration (VLSI) chips reverse engineering** of digital logic in chips.

- ∼70k LoC
- Supports Mac, Linux & Windows,
- Qt based,
- Multi-language support,
- Gate definition,
- Gate template, via & wire matching,
- Rule checks,
- ...



History

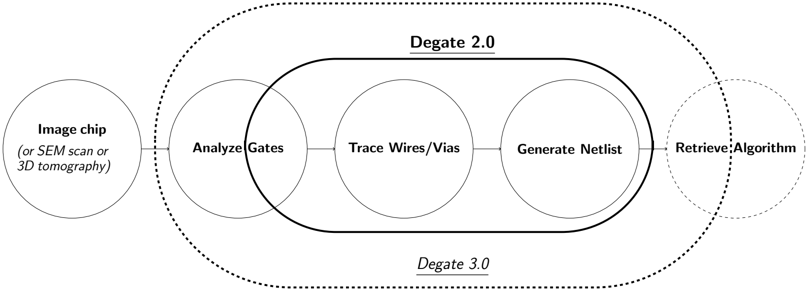
A long story, with **technical debt** and **major IC evolution** (in transistor count), along with a **small community**.



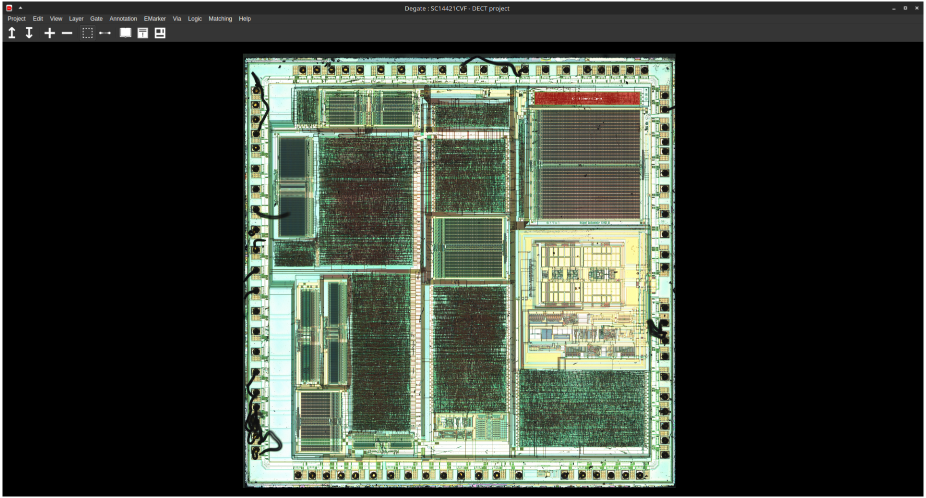
Usage

Degate help to reverse **VLSI chips** by creating an analyzed **gate library**, doing **template matching** to find gates instances from this library, **matching wires & vias**, **exporting netlist** and **navigating really huge images**.

Focus on **modern ICs** with **standard cells**, and supports **any 2D capture/imaging method** (SEM, optical...).



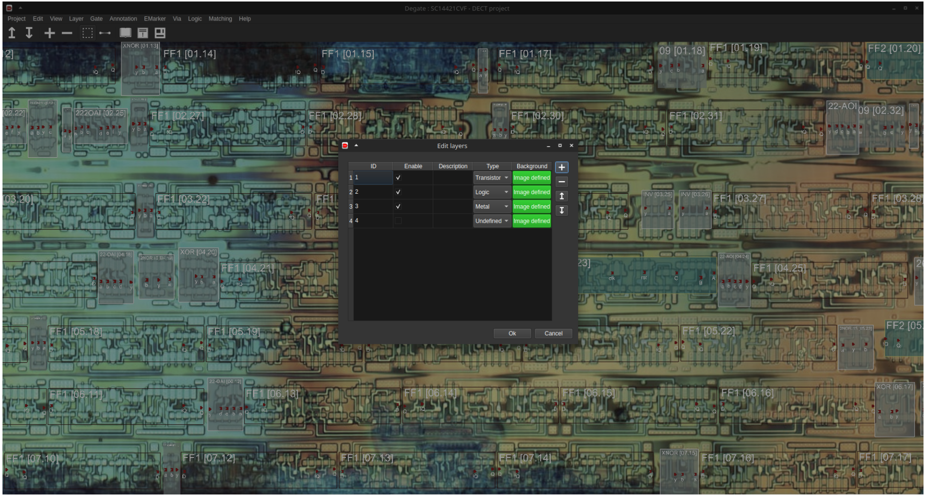
Small Demonstration



Overview of the chip, for zone of interest selection.

A sub-project can then be created on the zone of interest, and specific layers can be added (independent from the rest).

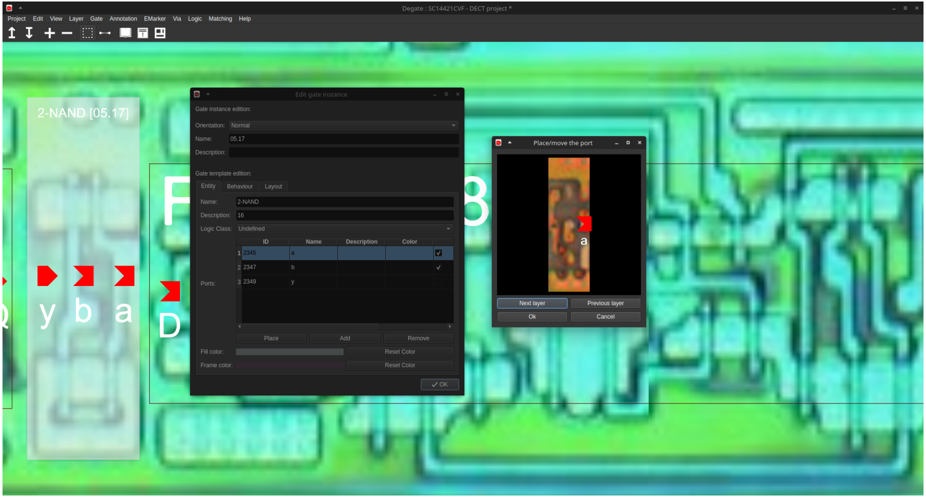
Small Demonstration



Each sub-project can contains multiple layers (pre-aligned images).

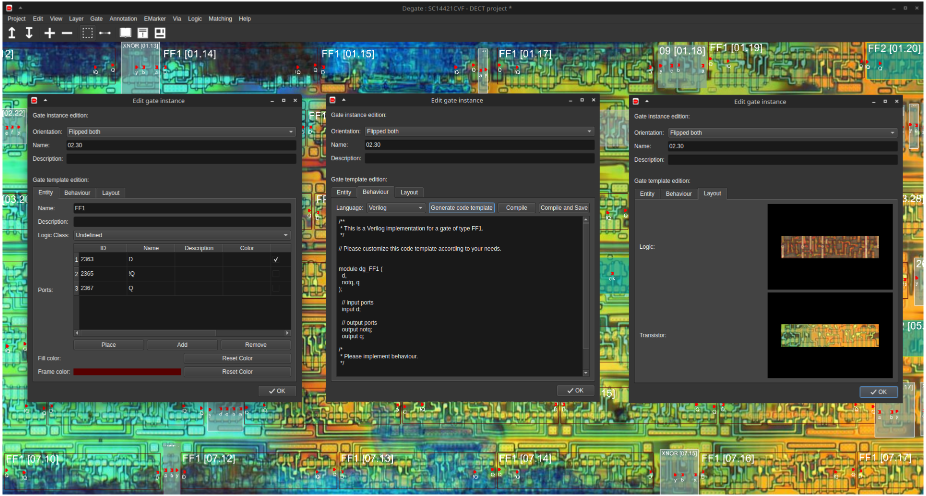
Two project mode: 1. For smaller images, will convert each images in Degate's format (for fast access) and 2. New (WIP, beta) mode for huge images (load only partial tiles in RAM, and doesn't change/import initial file).

Small Demonstration



Each gate can be described with VHDL/Verilog, have a list of port (placed on image), a type associated etc.

Small Demonstration



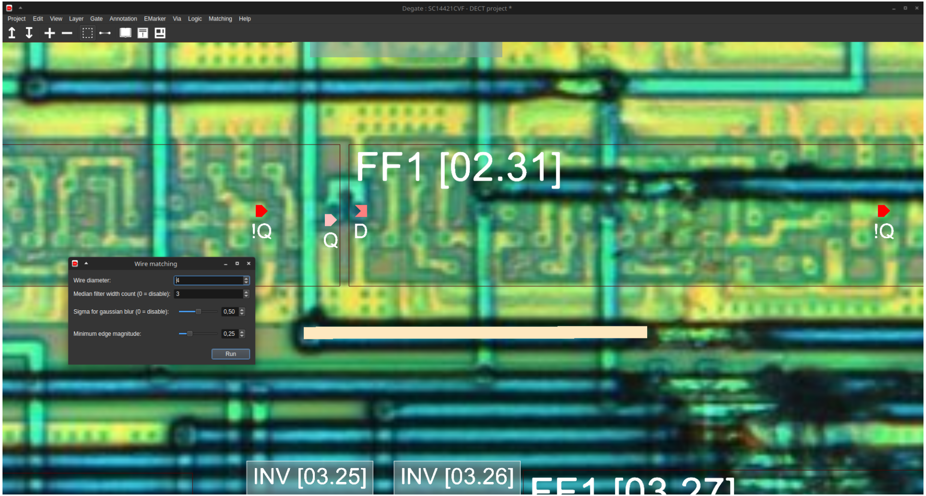
Each identified gate (from the gate library) can be matched manually or using template matching algorithms.

Small Demonstration

Template matching (will soon be ported to OpenCV) will use gate library to automate gate identification.

Currently it uses normalized cross-correlation (with some more steps).

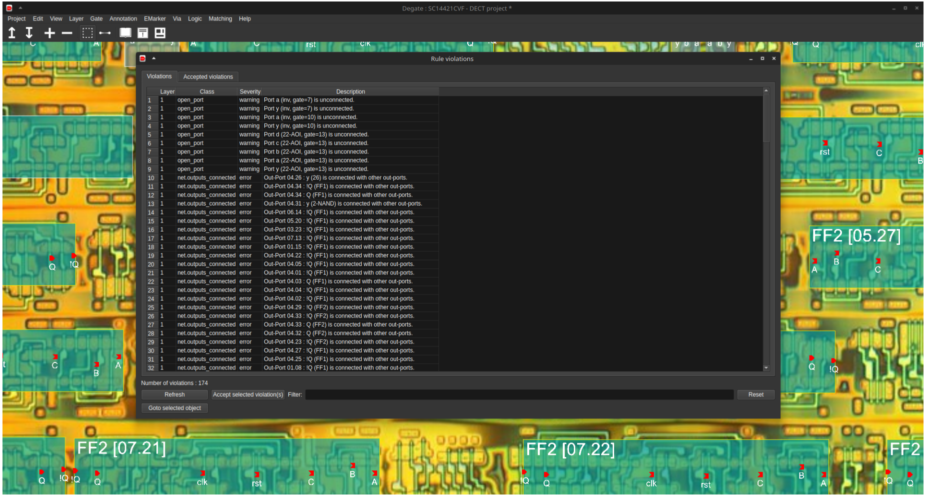
Small Demonstration



Wire matching, and specifically port inter-connection, is the real challenge (and very error prone).

Currently it uses zero crossing edge detection.

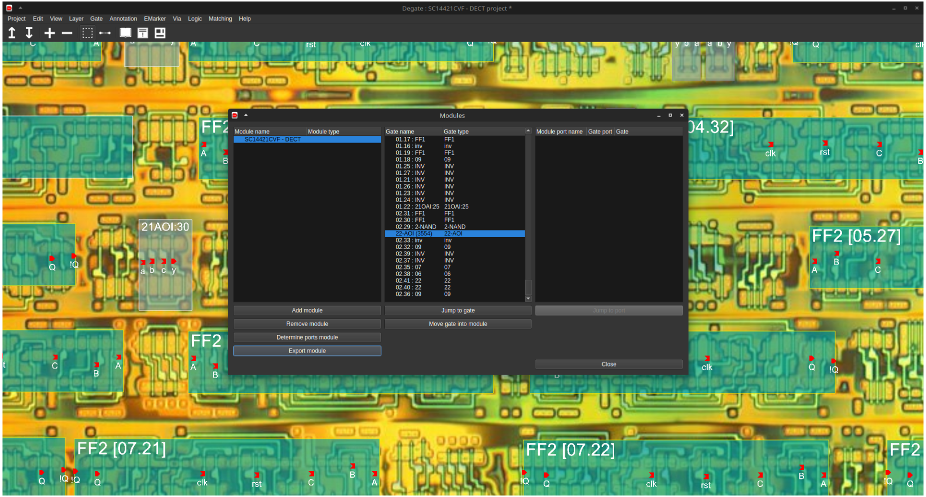
Small Demonstration



	Layer	Class	Severity	Description
1	1	open_port	warning	Port a (inv, gate=7) is unconnected.
2	1	open_port	warning	Port y (inv, gate=7) is unconnected.
3	1	open_port	warning	Port a (inv, gate=10) is unconnected.
4	1	open_port	warning	Port y (inv, gate=10) is unconnected.
5	1	open_port	warning	Port d (22-AOI, gate=13) is unconnected.
6	1	open_port	warning	Port c (22-AOI, gate=13) is unconnected.
7	1	open_port	warning	Port b (22-AOI, gate=13) is unconnected.
8	1	open_port	warning	Port a (22-AOI, gate=13) is unconnected.
9	1	open_port	warning	Port y (22-AOI, gate=13) is unconnected.
10	1	net.outputs_connected	error	Out-Port 04.26 : y (26) is connected with other out-ports.
11	1	net.outputs_connected	error	Out-Port 04.34 : !Q (FF1) is connected with other out-ports.
12	1	net.outputs_connected	error	Out-Port 04.34 : Q (FF1) is connected with other out-ports.
13	1	net.outputs_connected	error	Out-Port 04.31 : y (2-NAND) is connected with other out-ports.
14	1	net.outputs_connected	error	Out-Port 06.14 : !Q (FF1) is connected with other out-ports.
15	1	net.outputs_connected	error	Out-Port 05.20 : !Q (FF1) is connected with other out-ports.
16	1	net.outputs_connected	error	Out-Port 03.23 : !Q (FF1) is connected with other out-ports.
17	1	net.outputs_connected	error	Out-Port 07.13 : !Q (FF1) is connected with other out-ports.
18	1	net.outputs_connected	error	Out-Port 01.15 : !Q (FF1) is connected with other out-ports.
19	1	net.outputs_connected	error	Out-Port 04.22 : !Q (FF1) is connected with other out-ports.
20	1	net.outputs_connected	error	Out-Port 04.05 : !Q (FF1) is connected with other out-ports.
21	1	net.outputs_connected	error	Out-Port 04.01 : !Q (FF1) is connected with other out-ports.
22	1	net.outputs_connected	error	Out-Port 04.03 : Q (FF1) is connected with other out-ports.
23	1	net.outputs_connected	error	Out-Port 04.04 : !Q (FF1) is connected with other out-ports.
24	1	net.outputs_connected	error	Out-Port 04.02 : !Q (FF1) is connected with other out-ports.
25	1	net.outputs_connected	error	Out-Port 04.29 : !Q (FF2) is connected with other out-ports.
26	1	net.outputs_connected	error	Out-Port 04.33 : !Q (FF2) is connected with other out-ports.
27	1	net.outputs_connected	error	Out-Port 04.33 : Q (FF2) is connected with other out-ports.
28	1	net.outputs_connected	error	Out-Port 04.32 : Q (FF2) is connected with other out-ports.
29	1	net.outputs_connected	error	Out-Port 04.23 : !Q (FF2) is connected with other out-ports.
30	1	net.outputs_connected	error	Out-Port 04.27 : !Q (FF1) is connected with other out-ports.
31	1	net.outputs_connected	error	Out-Port 04.25 : !Q (FF1) is connected with other out-ports.
32	1	net.outputs_connected	error	Out-Port 01.08 : !Q (FF1) is connected with other out-ports.

Helpers are available, like rudimentary (but to be improved) rule checking (e.g. for coherency).

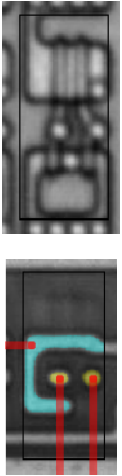
Small Demonstration



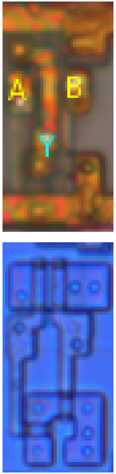
Everything can be organized in "module", exported individually (in Verilog/VHDL), etc... "Divide et impera".

Engineering Challenges

- Gate template, wires & vias **matching**.
- Very **huge images** handling.
- **Error** recovery/acceptance/identification.
- Multiple possible **image format** (e.g. .tiff, .png...) & **image source** (e.g. SEM, confocal...).
- 10+ years **old software** (mix of old & new C++).
- **Collaborative** analysis.
- Integrated **gate analyzer**.
- Explicit full **netlist exporter**.



MIFARE NAND[2]



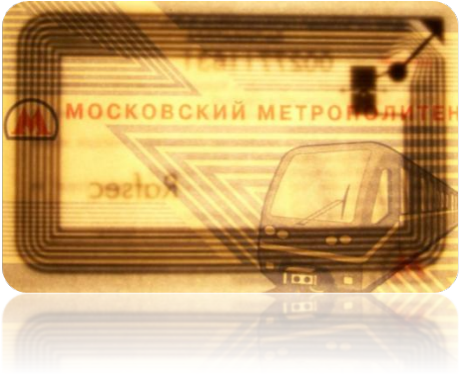
LEGIC NAND[2]

Research Challenges

- **3D capture**, imply rethinking Degate (New 3D mode? New software? Really accessible?), and **new algorithms** (e.g. for matching, tracing and gate identification).
- **Machine learning**/better algorithms for:
  - Auto-**vectorization** ;
  - Gate auto **identification** (from vectorized analysis) ;
  - Gate auto **wiring** ;
  - Auto vias & wires **identification**.
- Take advantage of certain capture methods such as **SEM** which makes **automation easier**.
- Making the **field more accessible** (more automation, new abstractions for analysis, communication...).
- Use Degate for **advanced analysis** and **published results**.

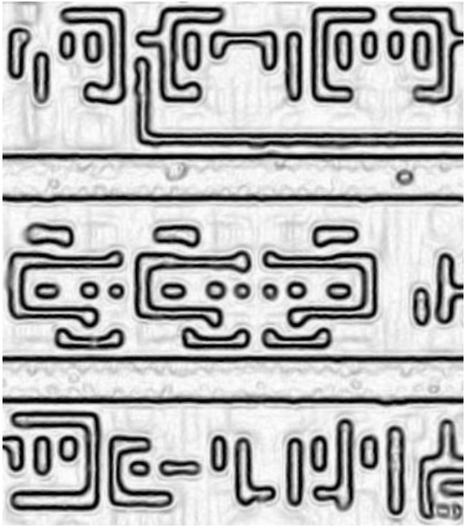
MIFARE Classic Chip [2]

- **RFID card** from NXP launched in 1994.
- Used the **Crypto1 cypher** (until MIFARE Classic EV1, that are using **Hitag2** cipher).
- **Proprietary encryption** algorithm (stream cipher), security by obscurity.
- Cryto1 cipher is only **implemented in hardware**.
- Used (back in 2008) in more than **3.5 billions cards** (including many building access control systems).



A **huge target** with a **suspicious cypher** and **security standards**?

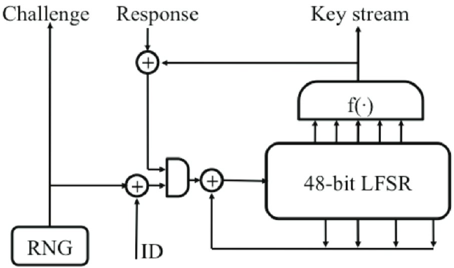
Degate's origins [5]



- K. Nohl & Starbug **reverse-engineered the Crypto1 cypher** from MIFARE Classic chip in 2007.
- Used **acetone** to dissolve the RFID cards.
- Used **manual polishing** for delayering.
- Image a total of **6 layers**.
- Identify zone of interest, **searching for 48-bit register** & group of XOR gates.
- Used **standard optical microscope** (500x) & hugin tool for stitching.
- Identified **around 70 types of gates**.
- Used **home-made scripts** (which became the base of Degate) for **template matching** to identify all gates.
- **Manually** reconstructed **connections** between gates.
- Made a **script** to help detecting **wires** & **vias**.

Consequences [5]

- Using the reverse-engineering results and protocol analysis, authors found **multiple weakness** in the cipher:
  - The cipher is vulnerable to **brute force** attack, key is too small.
  - RNG is predictable, it uses a 16-bit LFSR (linear feedback shift register) **initialized with constant value** and reset at each power-up.
  - There is **only one secret key** for each ID that can result to a specific session key, and all shifts are linear.
- Meaning that just by **sniffing interactions** with the card and the reader, we can compute the key and **retrieve all the data** of the card.
- NXP release a retro-compatible & "hardened" version of the Cipher (Hitag2), which was also weak, MIFARE Classic were **"discontinued" in 2015**.

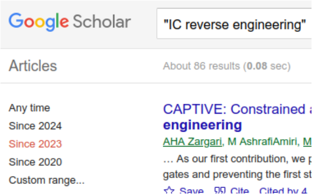


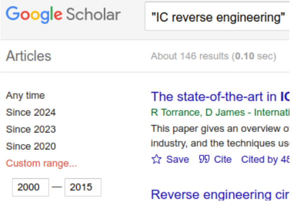
- Authors **analyzed other RFID devices** after.
- **Degate was created** from this analysis, used for other RFID devices reverse-engineering and open-sourced in 2008.

Future of Silicon Chip RE

- **Simpler** and **cheaper** IC capture (decap & delayer).
- Making the **field more accessible** (communication, more real-life and useful example/reference analysis...).
- **Shared and open** library of **chips captures** (∼zeptobar & siliconpr0n + SiliconZoo).
- **Machine learning** to automate even more analysis steps (*gate identification*, *wire extract*, *algorithm retrieving & analysis*)?

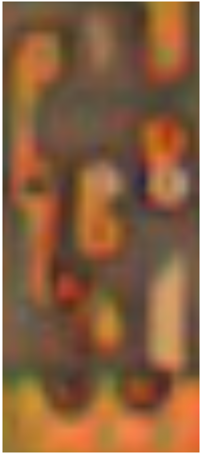
There is **2 EU projects** running around **ICs reverse-engineering**, but no information on tools, process and analysis **sharing**.





Which gate is this?

Transistor layer



Logic layer

Metal layer

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