COLD BOOT ATTACK on DDR2 and DDR3 RAM

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About

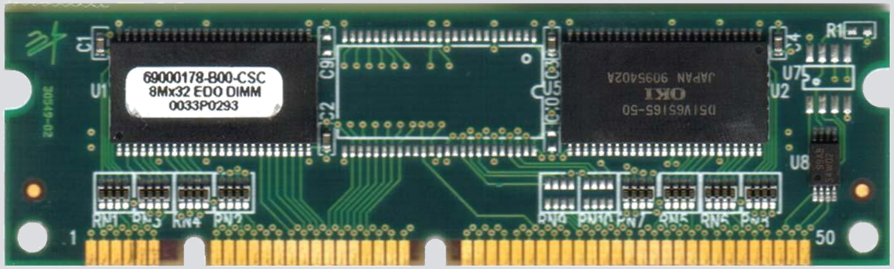
- Simon Lindenlauf
  - former BSc, now Master student at Aachen University of Applied Sciences (FH Aachen)
  - cold boot: topic of his bachelor thesis
- Marko Schuba
  - professor at FH Aachen (computer science)
  - topics of interest: security, forensics
- Hans Höfken
  - researcher at FH Aachen
  - topics of interest: practical stuff, ethical hacking etc.

Agenda

- What is a cold boot attack?
- Previous work by others
- Experiments
- Results
- Conclusions

DRAM

- DRAM = Dynamic Random-Access Memory
  - is a type of RAM
  - each bit stored in separate capacitor within integrated circuit (states: charged / discharged)

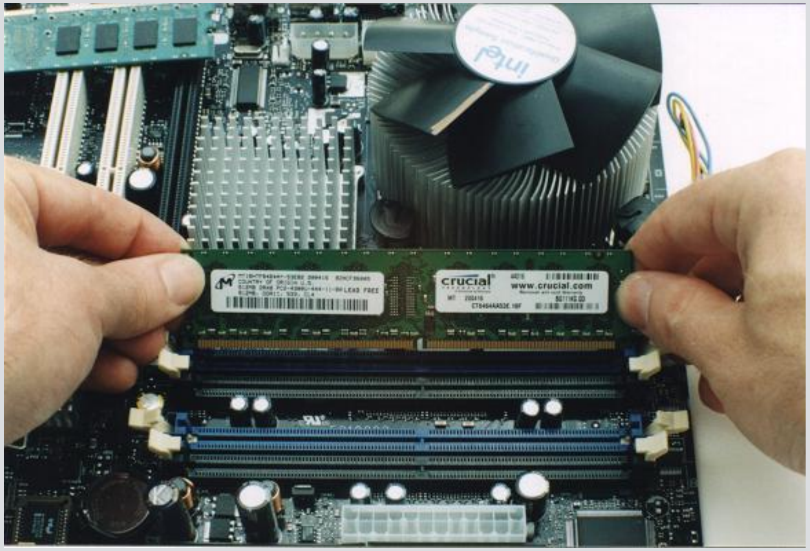


http://www.certificationkits.com/cisco-2600-32mb-dram/

- Leakage and refresh
  - capacitors leak, i.e. they slowly discharge
  - periodic refresh necessary (memory is “dynamic”)
- DRAM is main memory in computers today
  - high density, compared to static RAM

DDR SDRAM*

- DDR SDRAM is a widely used DRAM type
  - Types: DDR1, DDR2, DDR3 and recently DDR4
  - Have different peak transfer rates
    - basically doubling it with each generation
  - Most computers today use DDR2 or DDR3 SDRAM



http://www.ifitjams.com/ibuild3.htm

* Double data rate synchronous dynamic random-access memory

Refresh Rates & Retention Times

- As mentioned before:
  memory cells leak and thus require refresh

- Refresh rate depends on temperature
  - up to 85°C (185°F): 64 ms (standard refresh time)
  - between 85°C (185°F) and 95°C (203°F): 32 ms
  - obviously: leakage of cells increases with temperature

  - 64 ms refresh threshold to be on the safe side...
    - e.g. tests with DDR3
    - 45°C (113°F)
    - retention time for all cells >= 1.5 s

→ cooling RAM increases retention time

What is cold boot?

- Two options for rebooting a machine
  - cold reboot (or cold boot, hard boot)
  - warm reboot (or soft reboot)

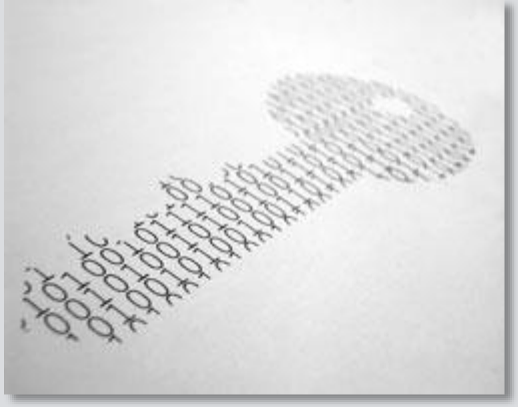
- Warm reboot (simplified)
  - restarting machine while it is powered on
    - e.g. Ctrl-Alt-Del on Windows, kexec on Linux
- Cold boot (simplified)
  - restarting machine from a power-less state
    - disconnecting cord/battery and starting machine again

What is a cold boot attack?

- Basic idea
  - DRAM memory content can be extracted after power has been cut
  - the lower the temperature of the DRAM the higher the probability that memory is unchanged
- Two ways to do it…memory dump can be done
  - on the original machine
    - DRAM stays where it is
    - original machine is cold booted
  - or on a different machine
    - DRAM is removed and plugged into a different computer
    - different computer is cold booted

Why all this?

- Main purpose: recovery of hard disk encryption key
  - Case: You are a digital forensics investigator
    - running machine which uses hard disk encryption
  - Machine not screen-locked: simple
  - Machine is screen-locked (& password unknown)
    - cannot simply copy disk
    - cannot shut down machine (& take out hard disk)
    - decryption key is in RAM:
      but as machine is locked, no way to
      dump image from the machine directly
  - Cold boot attack can help
    - attack provides an image of the RAM
    - might contain errors…
      but still keys can be recovered



http://www.computerweekly.com/news/2240118660/
IT-departments-risk-losing-responsibity-for-IT-security

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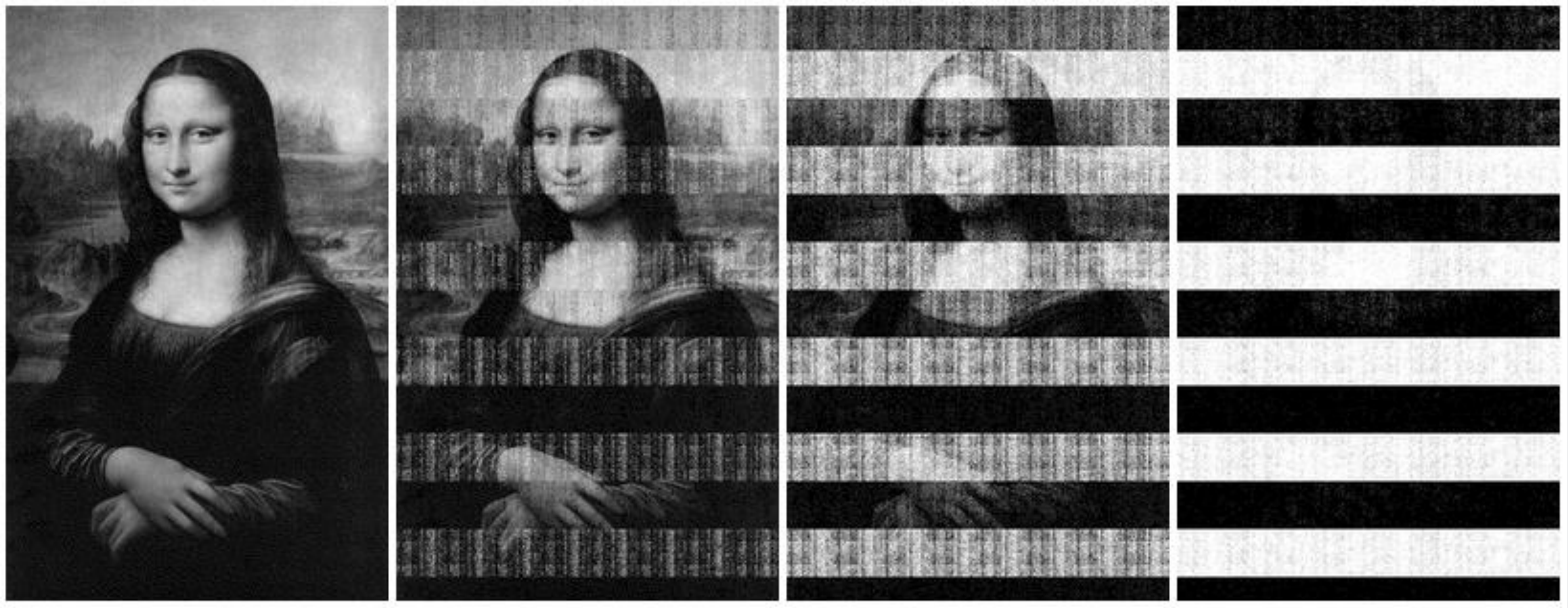
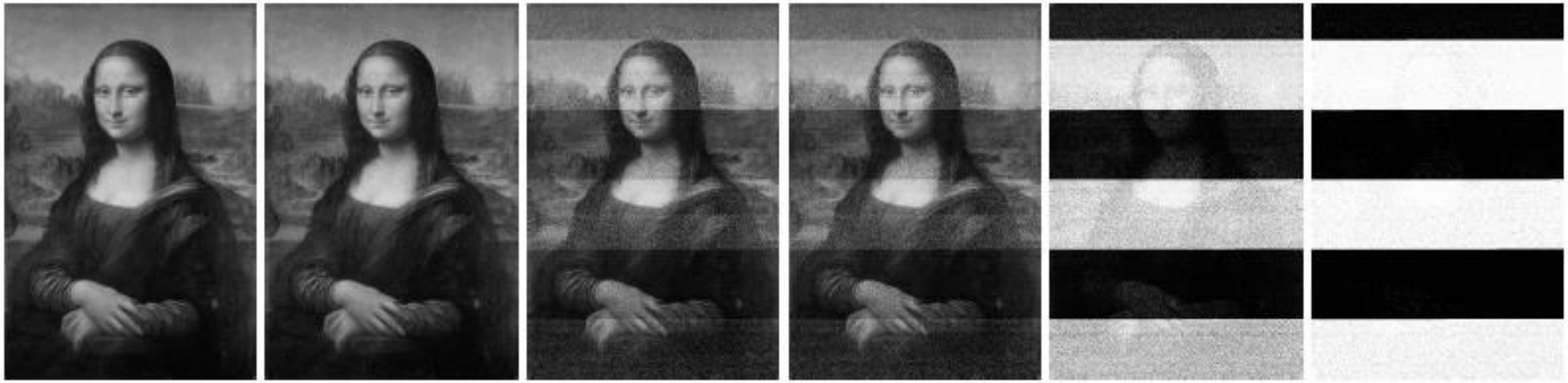
Lest We Remember...

- Halderman et al. published work on Cold Boot Attacks on Encryption Keys at USENIX Security '08
  - DDR and DDR2 SDRAM



On the Practicability of Cold Boot...

- 2013 Gruhn and Müller provide results for different DDR types 1, 2 and 3
  - Result: „we could not reproduce cold boot attacks against modern DDR3 chips“



(a) 0 sec / 100% (b) 2 sec / 99.2% (c) 3 sec / 93.4% (d) 4 sec / 93.1% (e) 5 sec / 61.4% (f) 6 sec / 51.9%

Figure 2: A picture of the Mona Lisa being recovered from system C's RAM at normal operational temperature of 20 to 25 °C after different amounts of time. Each picture's caption includes the percentage of *correct* bits that were recovered.

So, no cold boot attack on DDR3?

- Let‘s try it out...
  - What could be done differently?
  - Obvious... different picture...

Mona ⇨ Lena

http://en.wikipedia.org/wiki/Lenna

So, no cold boot attack on DDR3?

- Let‘s try it out...
  - What could be done differently?
  - Obvious... different picture...

    Mona ⇨ Lena
  - Ok, maybe something else...

    Mainboard
- But first a step back...

http://www.aliexpress.com/item-img/For-ASUS-60-N3GMB1800-B02-Laptop-motherboard-mainboard-K53SV-REV-3-0-45-days-warranty-works/1866829087.html#

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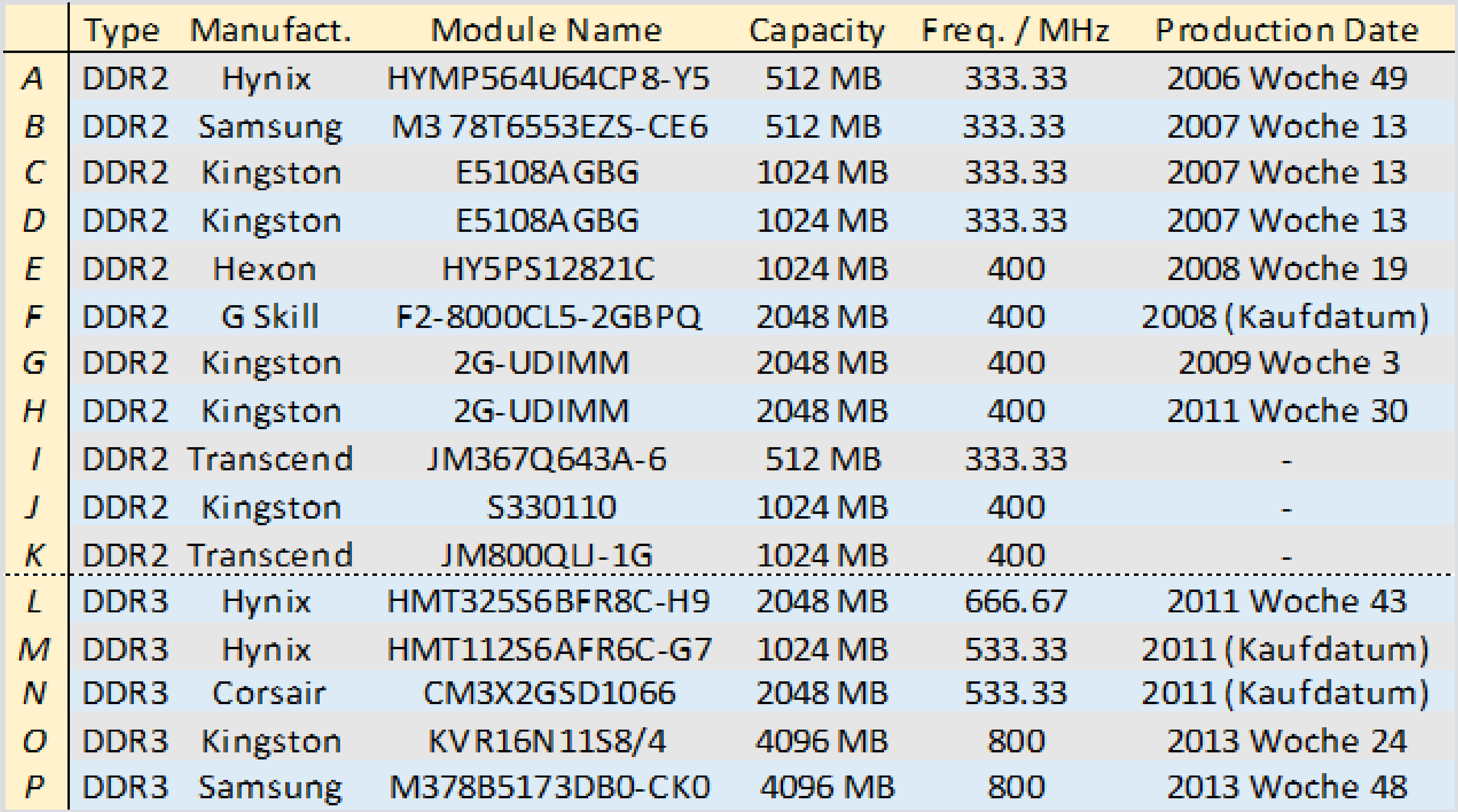
Considerations

- Cold boot attack results depend on
  - DRAM types ⇨ DDR2 and DDR3
  - DRAM manufacturer ⇨ 7 different manufacturers
  - individual DRAM ⇨ 16 different ones tested

Module Overview

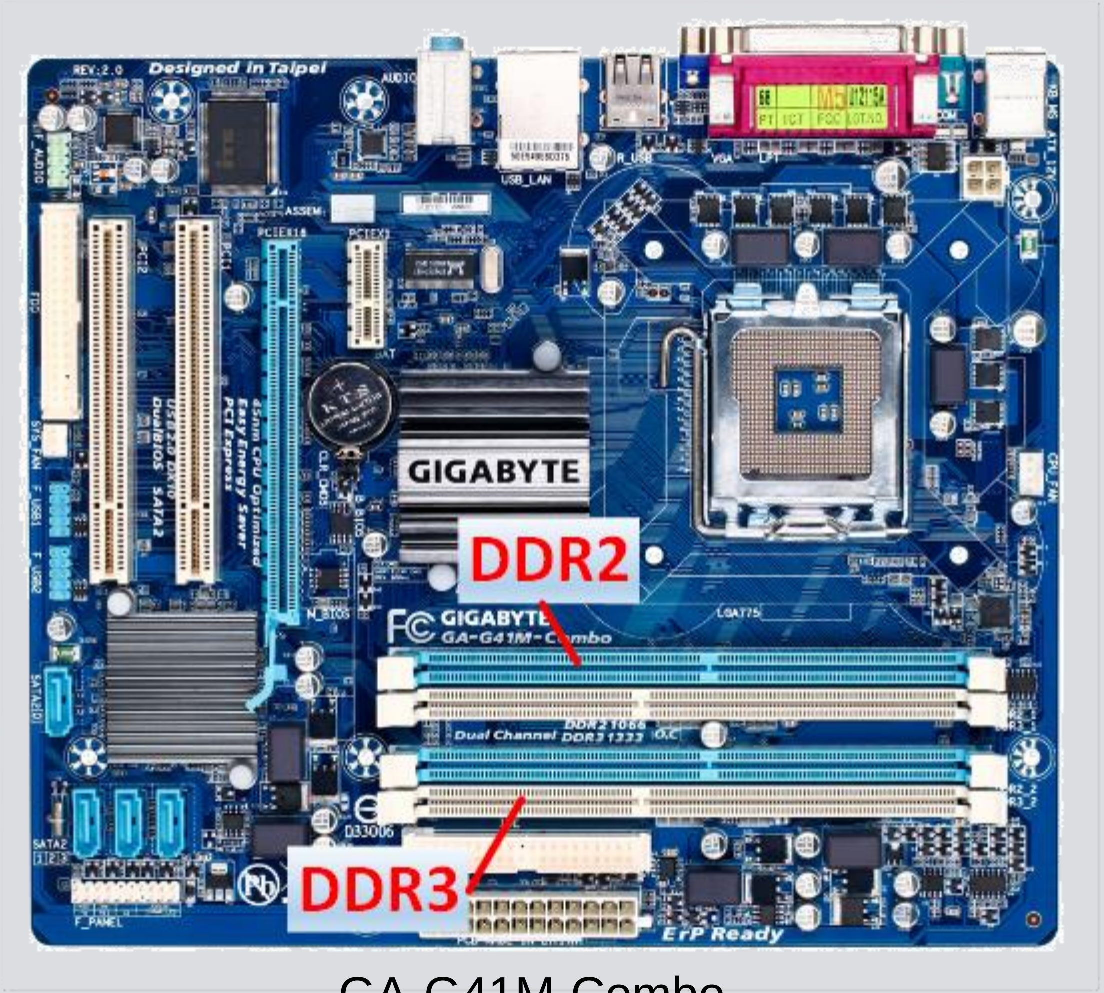


	Type	Manufact.	Module Name	Capacity	Freq. / MHz	Production Date
A	DDR2	Hynix	HYMP564U64CP8-Y5	512 MB	333.33	2006 Woche 49
B	DDR2	Samsung	M378T6553EZS-CE6	512 MB	333.33	2007 Woche 13
C	DDR2	Kingston	E5108AGBG	1024 MB	333.33	2007 Woche 13
D	DDR2	Kingston	E5108AGBG	1024 MB	333.33	2007 Woche 13
E	DDR2	Hexon	HY5PS12821C	1024 MB	400	2008 Woche 19
F	DDR2	G Skill	F2-8000CL5-2GBPQ	2048 MB	400	2008 (Kaufdatum)
G	DDR2	Kingston	2G-UDIMM	2048 MB	400	2009 Woche 3
H	DDR2	Kingston	2G-UDIMM	2048 MB	400	2011 Woche 30
I	DDR2	Transcend	JM367Q643A-6	512 MB	333.33	-
J	DDR2	Kingston	S330110	1024 MB	400	-
K	DDR2	Transcend	JM800QU-1G	1024 MB	400	-
L	DDR3	Hynix	HMT325S6BFR8C-H9	2048 MB	666.67	2011 Woche 43
M	DDR3	Hynix	HMT112S6AFR6C-G7	1024 MB	533.33	2011 (Kaufdatum)
N	DDR3	Corsair	CM3X2GSD1066	2048 MB	533.33	2011 (Kaufdatum)
O	DDR3	Kingston	KVR16N11S8/4	4096 MB	800	2013 Woche 24
P	DDR3	Samsung	M378B5173DB0-CK0	4096 MB	800	2013 Woche 48

Considerations

- Cold boot attack results depend on
  - DRAM types ⇨ DDR2 and DDR3
  - DRAM manufacturer ⇨ 7 different manufacturers
  - individual DRAM ⇨ 16 different ones tested
  - mainboard ⇨ 2 different ones

Mainboards used



GA-G41M-Combo

Notebook ASUS P53E mainboard

Considerations

- Cold boot attack results depend on
  - DRAM types ⇨ DDR2 and DDR3
  - DRAM manufacturer ⇨ 7 different manufacturers
  - individual DRAM ⇨ 16 different ones tested
  - mainboard ⇨ 2 different ones
  - Multi Channel Mode? ⇨ if yes, several impacts
  - DRAM temperature ⇨ tested different ones
  - DRAM seconds w/o power ⇨ tested different ones
  - footprint of cold boot OS ⇨ the smaller the better

Procedure

- Steps of cold boot attack
  - original machine: prepare it with test data (Lena + x)
  - cold boot machine: prepare boot USB stick & connect it
  - original machine (running): adjust DRAM temperature (e.g. cool it to increase retention time)
  - original machine: power it down
    - unplug power cable
      (notebook: battery to be removed before)
  - `if` original ≠ cold boot machine `then` move DRAM
  - cold boot machine: power-on (booting from USB)
  - program on USB stick reads and stores RAM data
  - analyse RAM data (offline)

Procedure

- Cold boot attack procedure
  - prepare … l boot machine
  - prepare … na)
  - cool DR… (to incre…
  - power d…
    - remov…
    - unplu…
  - if origina… M
  - power-o… USB)
  - program on USB stick reads and stores RAM data
  - analyse RAM data (offline)

Cold boot attack

1. prepare data & USB
2. cool DRAM
3. power down
4. (move DRAM)
5. power-on & read data

Cold boot attack

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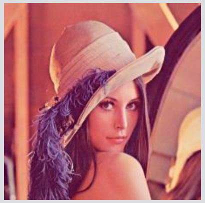
Prepare Test Data

- Task: same data in memory for each test
  - used small OS based on JamesM's kernel development tutorials (multiboot kernel) and GRUB bootloader
  - test data based on Lena image (X PixMap)
  - pixel area extracted and written to RAM (starting at fixed address)
  - additionally: 100 MB test file (starting at another fixed address)



Cold boot attack

1. prepare USB & data
2. cool DRAM
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Prepare Cold Boot USB

- Two small footprint OS (~ 2 MB) tested
  - msramdmp (Wesley McGrew; 32 bit OS)
    - used predominantly (single USB stick / multiple tests)
  - bios_memimage (Princeton University, 64 bit OS)
    - for DRAM > 4 GB
- When machine is cold booted from USB
  - both dump the RAM and save it to USB stick
  - msramdmp slightly modified to extract test data only
    - first 500 MB of DRAM
    - faster and sufficient for test data

Cold boot attack

1. prepare data & USB
2. cool DRAM
3. power down
4. (move DRAM)
5. power-on & read data

How to cool the DRAM?

- Option 1: move project to a cold location...
- Option 2: more cost efficient
  ⇨ cooling spray

://www.hotel-tenz.com/sport-freizeit/ski-cavalese-alpe-cermis.html

Cold boot attack

1. prepare data & USB
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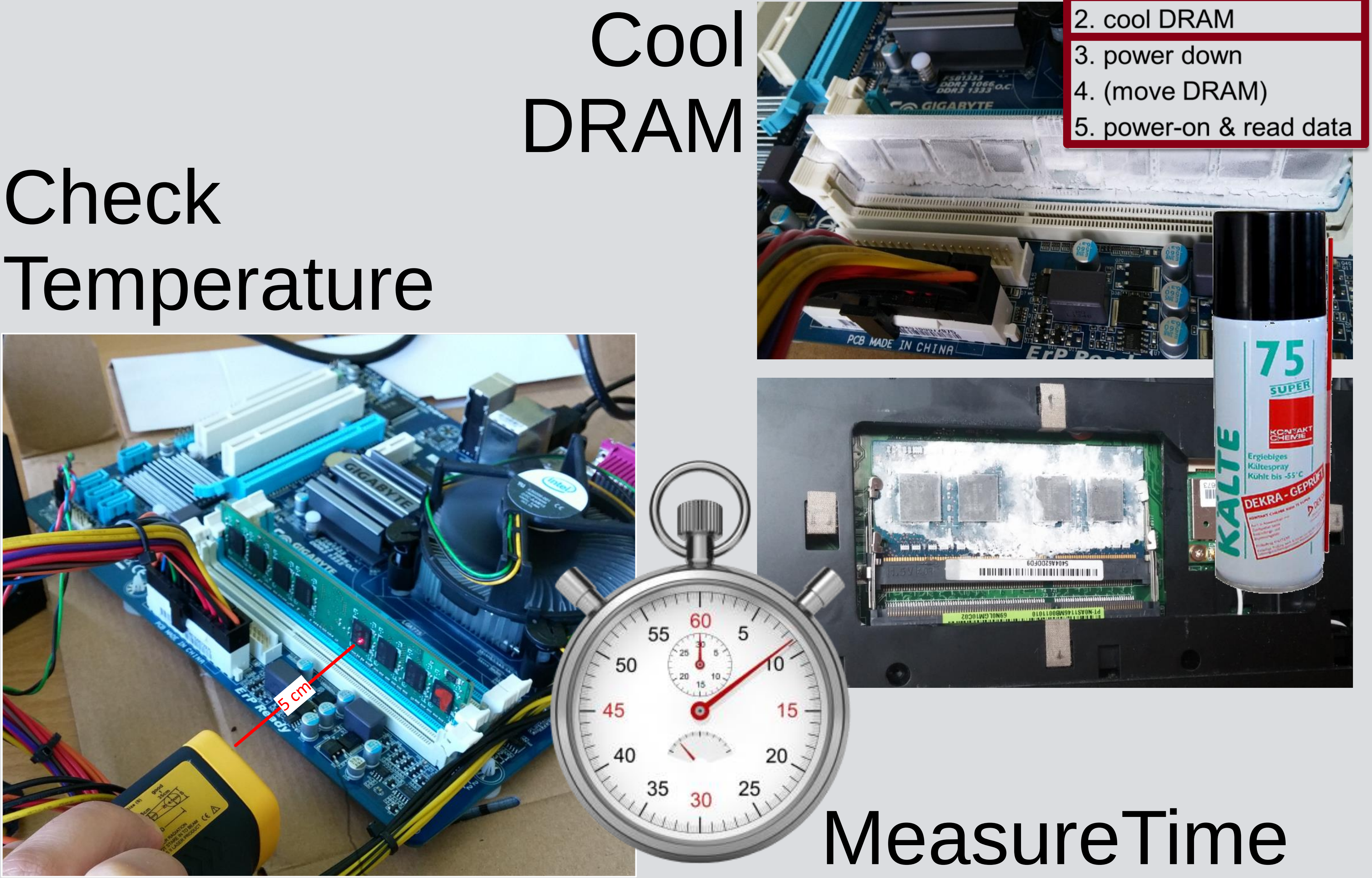
Cool DRAM

Check Temperature

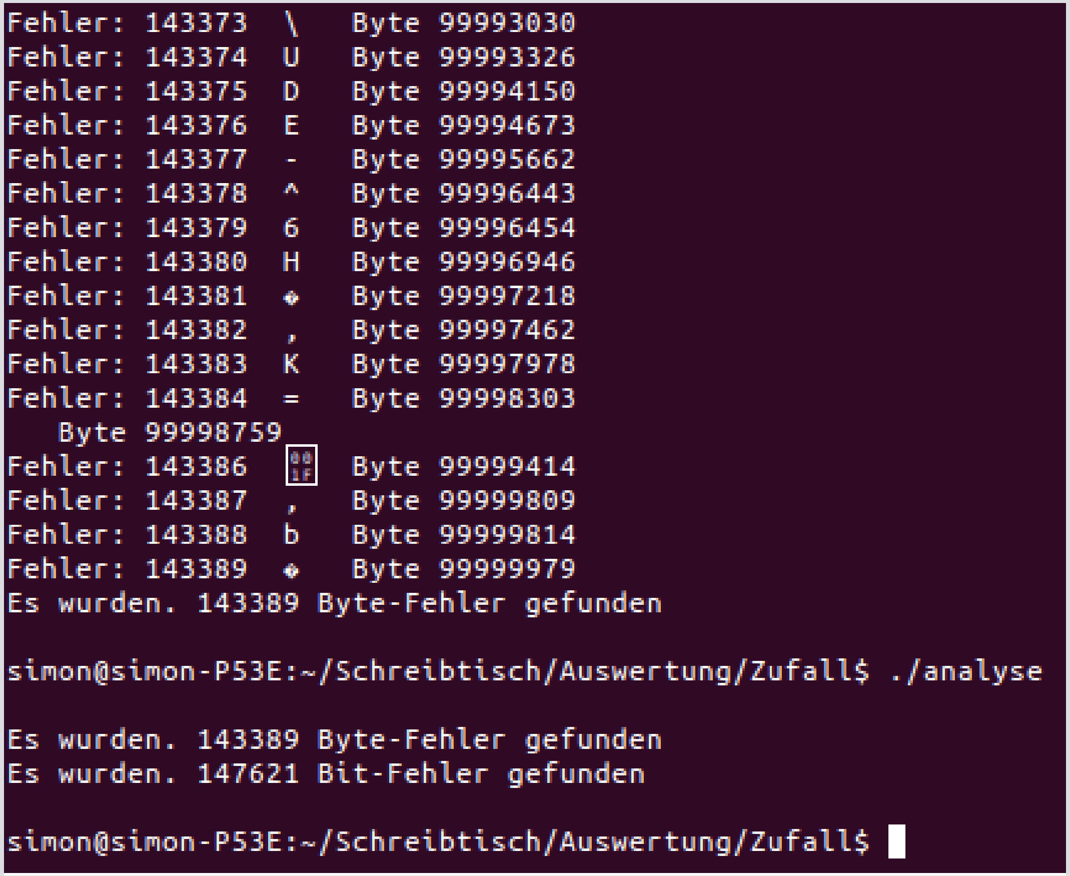


Measure Time

Cold boot attack
1. prepare data & USB
2. cool DRAM
3. power down
4. (move DRAM)
5. power-on & read data

Read & Analyse Data

- Determine byte & bit errors

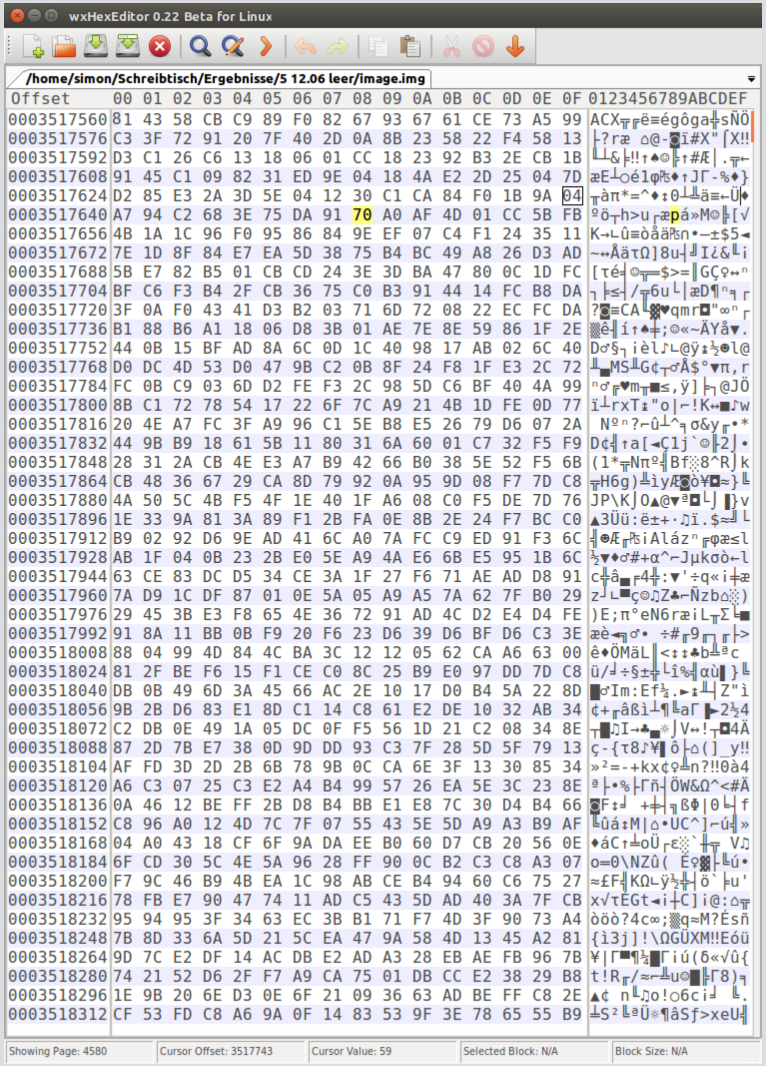


```
Fehler: 143373  \   Byte 99993030
Fehler: 143374  U   Byte 99993326
Fehler: 143375  D   Byte 99994150
Fehler: 143376  E   Byte 99994673
Fehler: 143377  -   Byte 99995662
Fehler: 143378  ^   Byte 99996443
Fehler: 143379  6   Byte 99996454
Fehler: 143380  H   Byte 99996946
Fehler: 143381  ◆   Byte 99997218
Fehler: 143382  ,   Byte 99997462
Fehler: 143383  K   Byte 99997978
Fehler: 143384  =   Byte 99998303
   Byte 99998759
Fehler: 143386  ␟   Byte 99999414
Fehler: 143387  ,   Byte 99999809
Fehler: 143388  b   Byte 99999814
Fehler: 143389  ◆   Byte 99999979
Es wurden. 143389 Byte-Fehler gefunden

simon@simon-P53E:~/Schreibtisch/Auswertung/Zufall$ ./analyse

Es wurden. 143389 Byte-Fehler gefunden
Es wurden. 147621 Bit-Fehler gefunden

simon@simon-P53E:~/Schreibtisch/Auswertung/Zufall$ 
```



wxHexEditor 0.22 Beta for Linux

/home/simon/Schreibtisch/Ergebnisse/5 12.06 leer/image.img

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0003518088 87 2D 7B E7 38 0D 9D DD 93 C3 7F 28 5D 5F 79 13 ç-{τ8♪¥▌ô├⌂(]_y‼
0003518104 AF FD 3D 2D 2B 6B 78 9B 0C CA 6E 3F 13 30 85 34 »²=-+kx¢♀╩n?‼0à4
0003518120 A6 C3 07 25 C3 E2 A4 B4 99 57 26 EA 5E 3C 23 8E ª├•%├Γñ┤ÖW&Ω^<#Ä
0003518136 0A 46 12 BE FF 2B D8 B4 BB E1 E8 7C 30 D4 B4 66 ◙F↕╛ +╪┤╗ßΦ|0╘┤f
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0003518296 1E 9B 20 6E D3 0E 6F 21 09 36 63 AD BE FF C8 2E ▲¢ n╙♫o!○6c¡╛ ╚.
0003518312 CF 53 FD C8 A6 9A 0F 14 83 53 9F 3E 78 65 55 B9 ╧S²╚ªÜ☼¶âSƒ>xeU╣
```

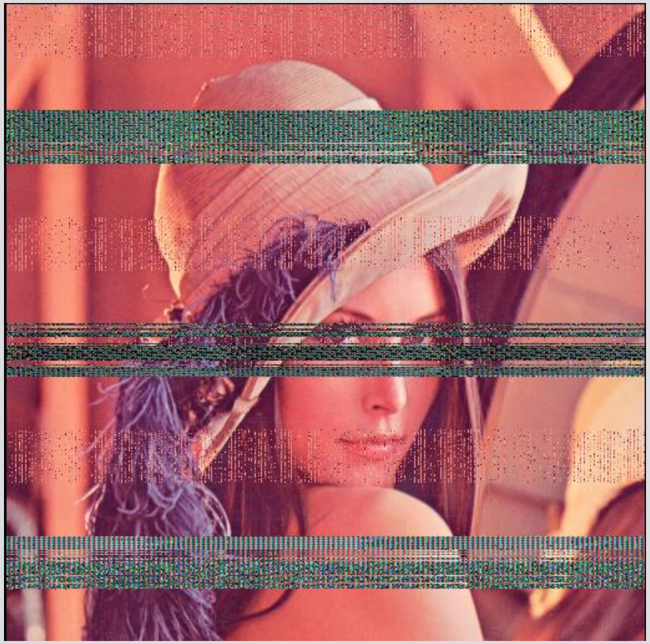
Showing Page: 4580 | Cursor Offset: 3517743 | Cursor Value: 59 | Selected Block: N/A | Block Size: N/A

Cold boot attack

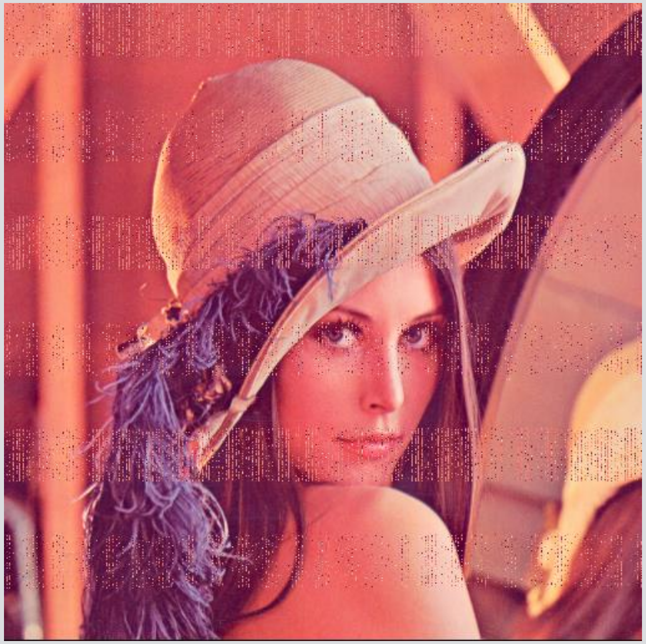
1. prepare data & USB
2. cool DRAM
3. power down
4. (move DRAM)
5. power-on & read data

Read & Analyse Data

- Determine byte & bit errors
- Reconstruct & view image

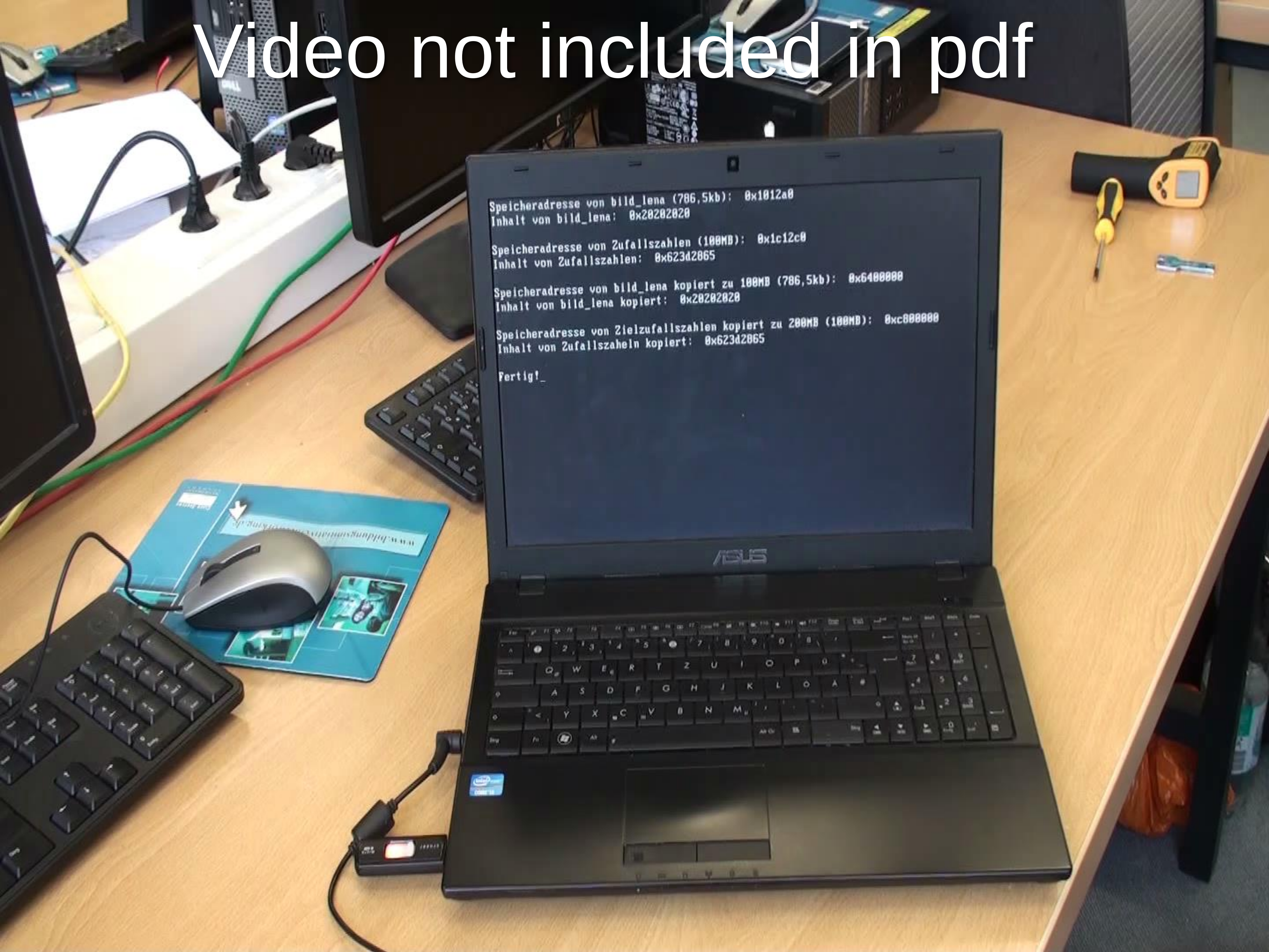


a) bit errors that change byte to quote character or null byte damage whole line



b) correction of quote characters and null bytes by one bit reduce this to pixel errors

Video not included in pdf



```
Speicheradresse von bild_lena (786,5kb):  0x1012a0
Inhalt von bild_lena:  0x20202020

Speicheradresse von Zufallszahlen (100MB):  0x1c12c0
Inhalt von Zufallszahlen:  0x623d2865

Speicheradresse von bild_lena kopiert zu 100MB (786,5kb):  0x6400000
Inhalt von bild_lena kopiert:  0x20202020

Speicheradresse von Zielzufallszahlen kopiert zu 200MB (100MB):  0xc800000
Inhalt von Zufallszaheln kopiert:  0x623d2865

Fertig!_
```

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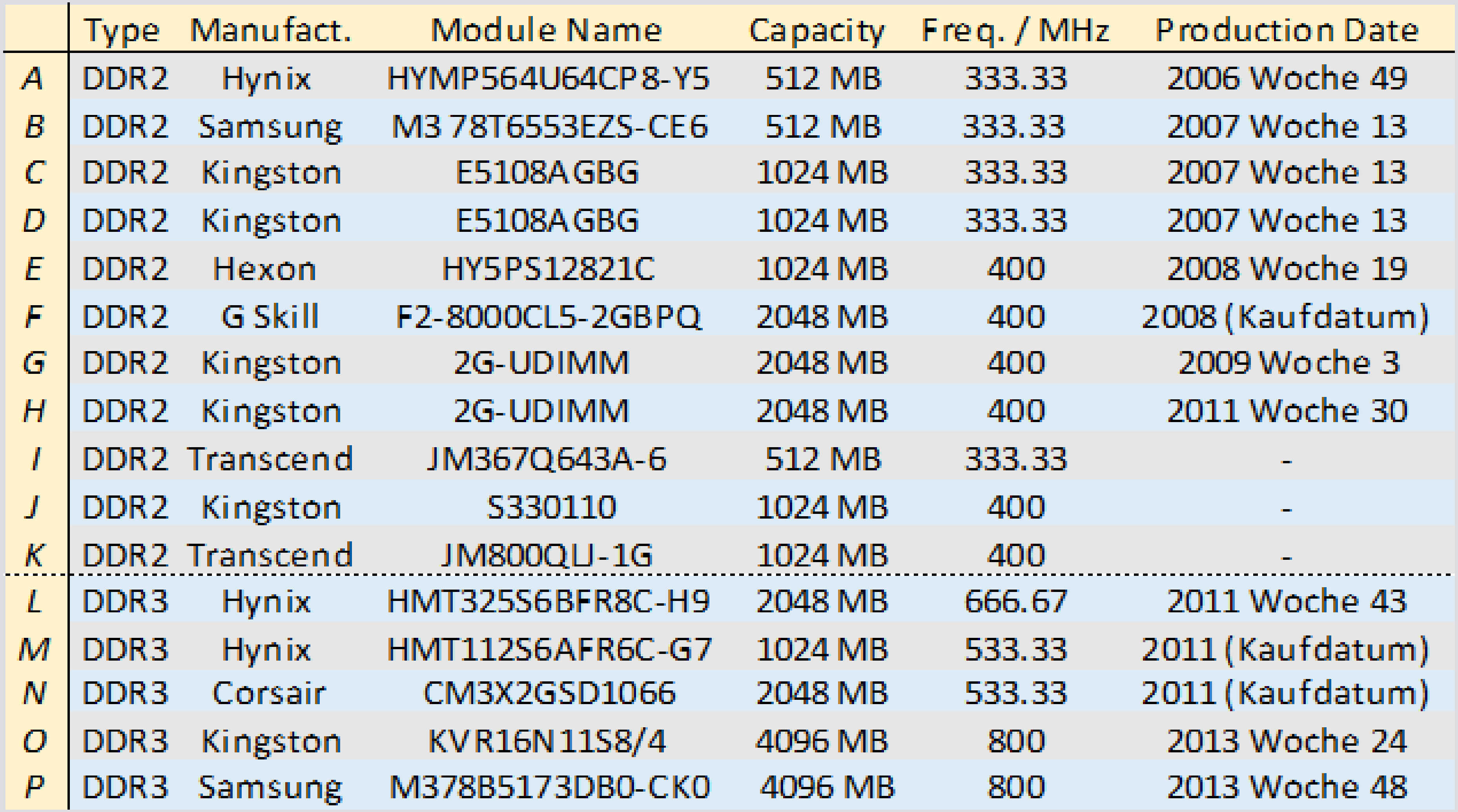

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C	DDR2	Kingston	E5108AGBG	1024 MB	333.33	2007 Woche 13
D	DDR2	Kingston	E5108AGBG	1024 MB	333.33	2007 Woche 13
E	DDR2	Hexon	HY5PS12821C	1024 MB	400	2008 Woche 19
F	DDR2	G Skill	F2-8000CL5-2GBPQ	2048 MB	400	2008 (Kaufdatum)
G	DDR2	Kingston	2G-UDIMM	2048 MB	400	2009 Woche 3
H	DDR2	Kingston	2G-UDIMM	2048 MB	400	2011 Woche 30
I	DDR2	Transcend	JM367Q643A-6	512 MB	333.33	-
J	DDR2	Kingston	S330110	1024 MB	400	-
K	DDR2	Transcend	JM800QU-1G	1024 MB	400	-
L	DDR3	Hynix	HMT325S6BFR8C-H9	2048 MB	666.67	2011 Woche 43
M	DDR3	Hynix	HMT112S6AFR6C-G7	1024 MB	533.33	2011 (Kaufdatum)
N	DDR3	Corsair	CM3X2GSD1066	2048 MB	533.33	2011 (Kaufdatum)
O	DDR3	Kingston	KVR16N11S8/4	4096 MB	800	2013 Woche 24
P	DDR3	Samsung	M378B5173DB0-CK0	4096 MB	800	2013 Woche 48

Selected Results DDR2

10s without power at -35°C to -30°C

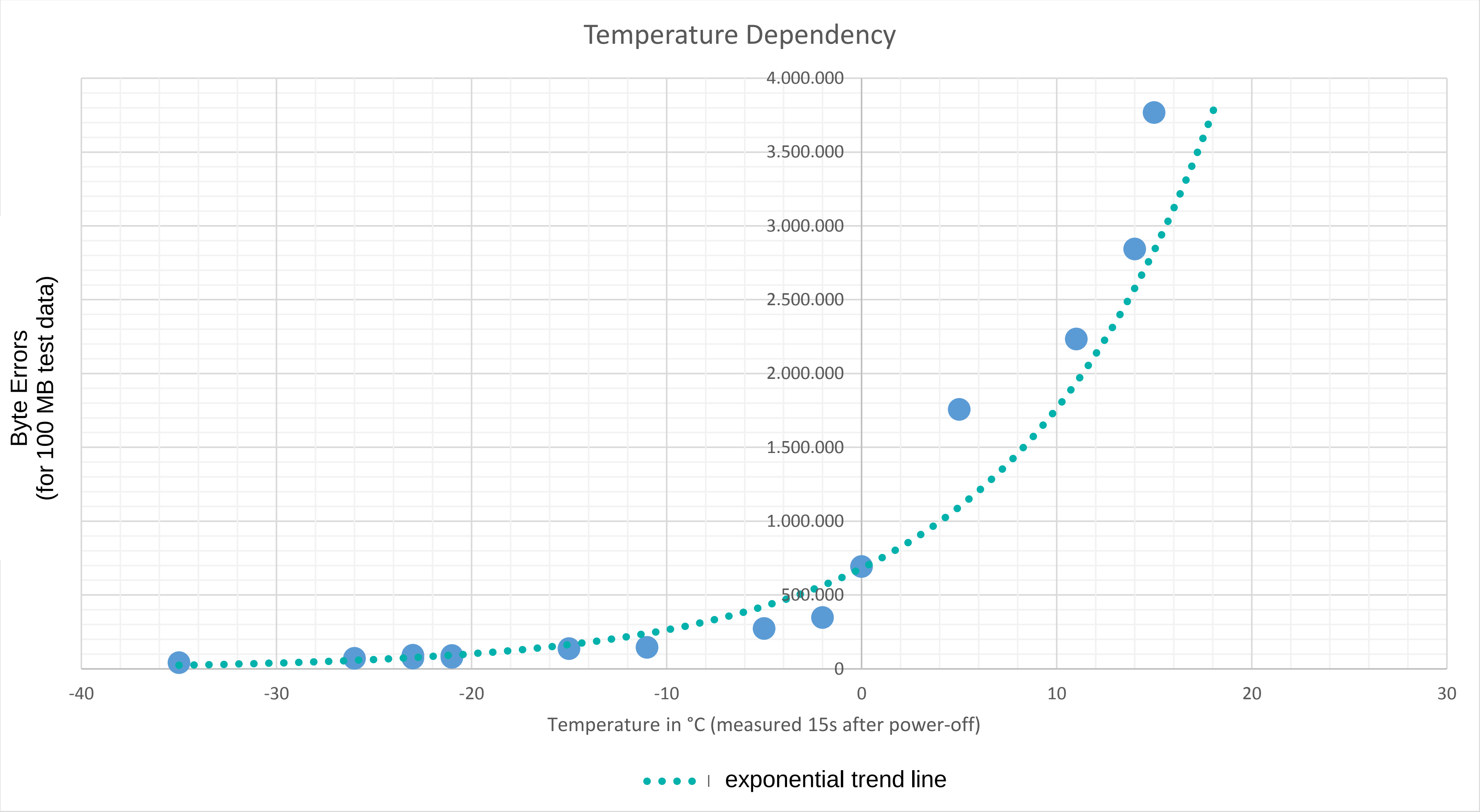
DDR2	RAM	Byte Errors	Bit Errors	Byte Error Rate	Bit Error Rate
1	B	236	236	0,000236%	0,000030%
2	F	2.204	2.212	0,002204%	0,000277%
3	G	3.675	3.943	0,003675%	0,000493%
4	C	82.539	85.766	0,0825%	0,0107%
5	H	239.263	558.522	0,239%	0,070%
6	D	729.380	795.702	0,729%	0,099%
7	J	2.248.293	2.477.976	2,248%	0,310%
8	I	4.763.617	7.862.582	4,764%	0,983%
9	A	12.870.663	28.379.907	12,87%	3,55%
10	E	20.997.916	71.909.648	21,00%	8,99%
11	K	35.475.736	88.992.338	35,48%	11,12%

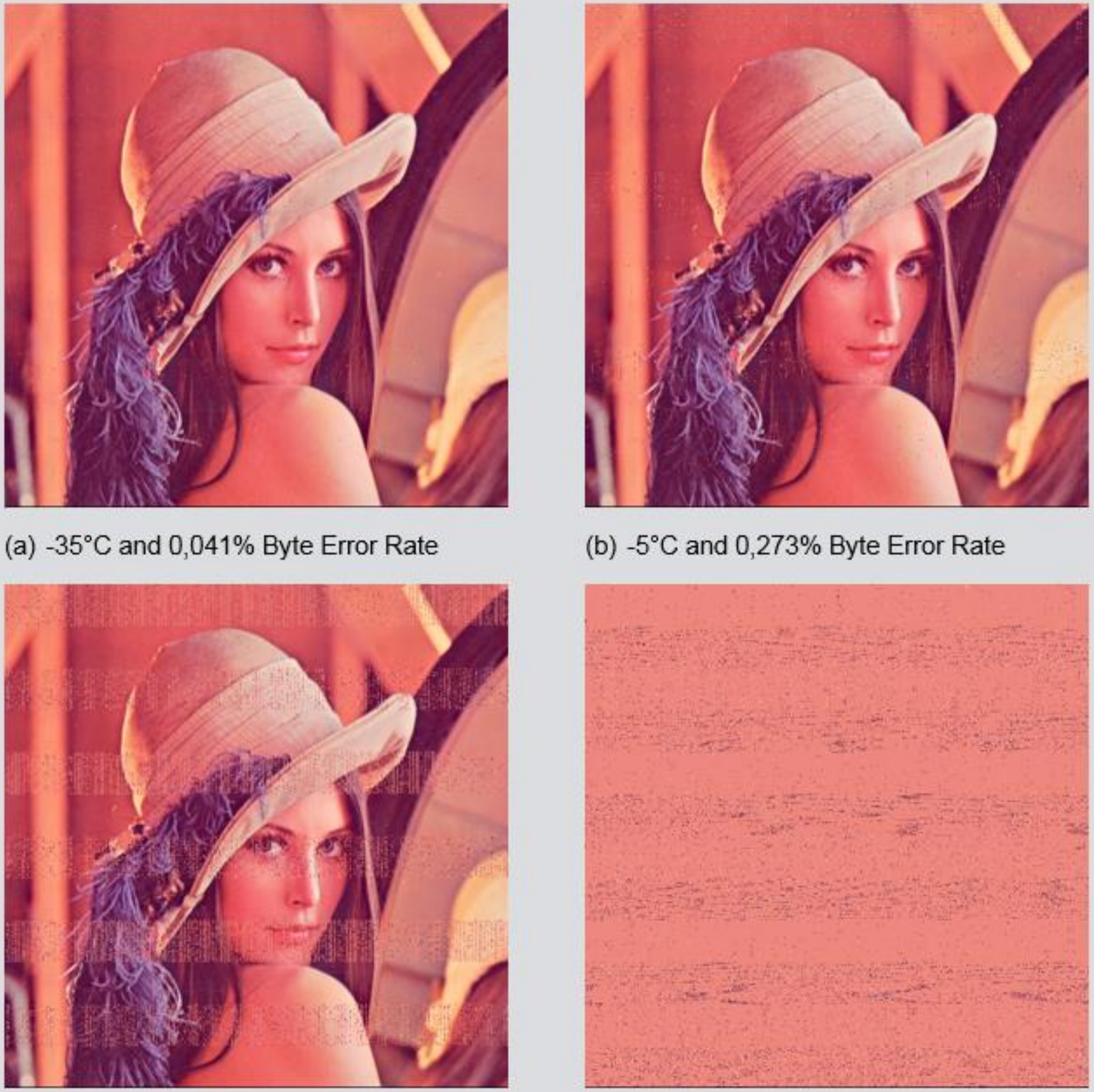
Selected Results DDR3

10s without power at -35°C to -30°C

DDR3	RAM	Byte Errors	Bit Errors	Byte Error Rate	Bit Error Rate
1	N	1.604	5.624	0,001604%	0,000703%
2	M	4.435	8.275	0,004435%	0,001034%
3	L	460.860	534.566	0,461%	0,067%

Error – Temperature Dependency





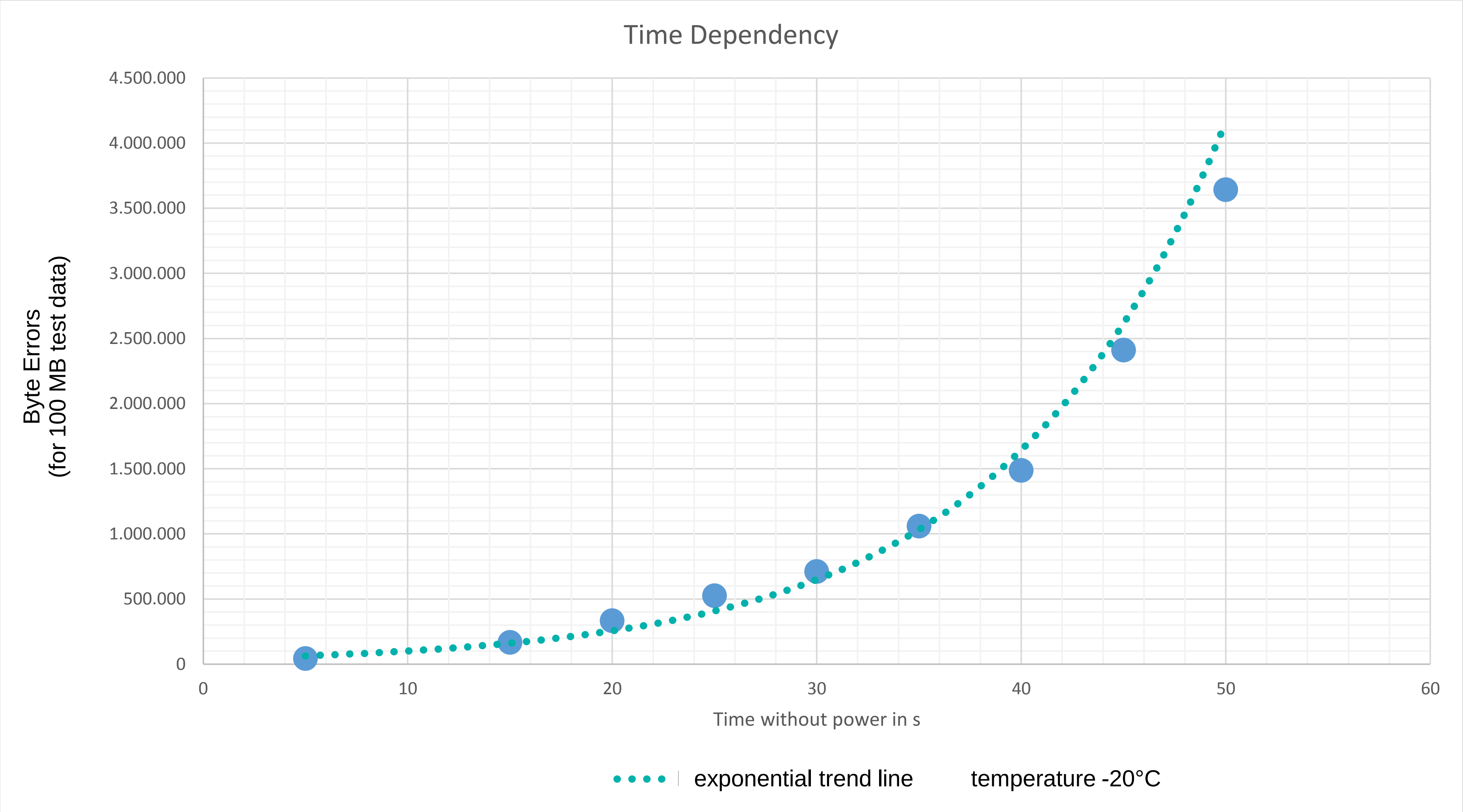
(a) -35°C and 0,041% Byte Error Rate

(b) -5°C and 0,273% Byte Error Rate

(c) +15°C and 1,756% Byte Error Rate

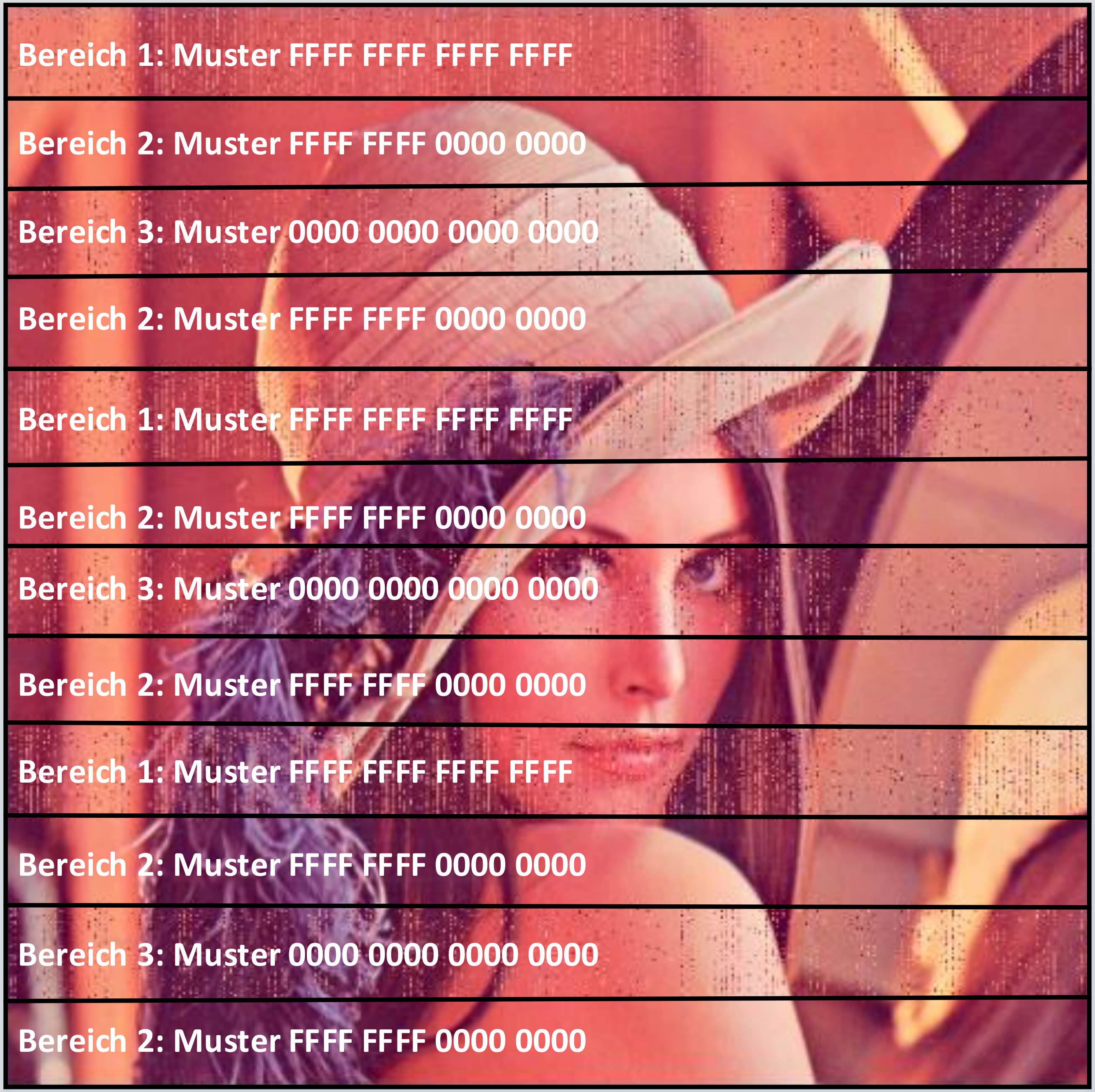
(d) +30°C and 34,284% Byte Error Rate

Error - Time Dependency



Error Patterns

- some DRAM show different error rates depending on ground state
- some areas error free
- reason not clear yet


Bereich 1: Muster FFFF FFFF FFFF FFFF
Bereich 2: Muster FFFF FFFF 0000 0000
Bereich 3: Muster 0000 0000 0000 0000
Bereich 2: Muster FFFF FFFF 0000 0000
Bereich 1: Muster FFFF FFFF FFFF FFFF
Bereich 2: Muster FFFF FFFF 0000 0000
Bereich 3: Muster 0000 0000 0000 0000
Bereich 2: Muster FFFF FFFF 0000 0000
Bereich 1: Muster FFFF FFFF FFFF FFFF
Bereich 2: Muster FFFF FFFF 0000 0000
Bereich 3: Muster 0000 0000 0000 0000
Bereich 2: Muster FFFF FFFF 0000 0000

Anti Cold Boot

- Enable POST in BIOS
  - overwrites complete RAM
- Password-protect boot device sequence
  - avoid booting of RAM dump software
- Password based pre-boot authentication
  - otherwise encryption key in RAM after restart
- Store encryption key outside RAM
  - e.g. possible in CPU registers
  - this even works if RAM is moved to different machine

Agenda

- What is a cold boot attack?
- Previous work by others
- Experiments
- Results
- Conclusions

Conclusions

- Cold boot attacks not as complicated as expected☺
  - could be feasible approach for digital forensics investigators

- Attacks on DDR3 are possible
  - admittedly, we have been lucky with the board…

Thank You

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