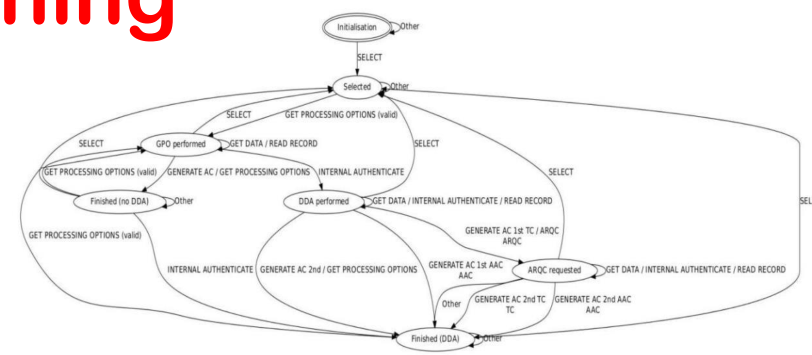
Software Security

1. LangSec

2. State machine learning



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TRU/e Master in Cyber Security

INPUT problems: forwarding flaws

malicious input

application

(Abuse of) a feature?

External service:
SQL database,
OS & file system,
some library,
MS Office, …

Examples:

SQL injection, XSS, OS command injection
path traversal, format strings, Word Macros, …

Detection:

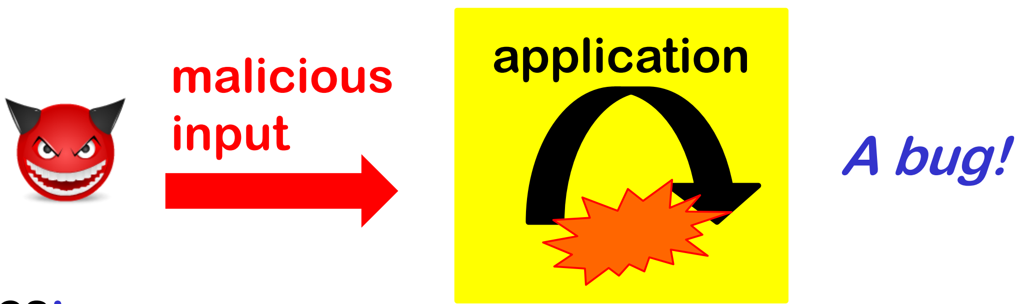
- negative tests (& fuzzing?)
- information flow analysis (dynamically, aka tainting)

Prevention:

- input validation
- context-sensitive output escaping
- information flow analysis (statically, eg. with typing)

To read: [LangSec revisited: input security flaws of the second kind, LangSec 2018]

INPUT problems: processing flaws



Examples:

bugs (esp buffer overflows) processing JPEG, PDF, SMS, ….
logical flaws, e.g. by-passing authentication checks

Detection:

- fuzzing (& negative tests?)
- …

Prevention:

- input validation?
- ….   *LangSec!   topic of 1st half of today's lecture*

LangSec (Language-Theoretic Security)

LangSec takes a systematic look at how to deal with input languages or formats to avoid typical input security problems

Root causes highlighted by LangSec community

1. **Applications have to handle data in *many* languages & formats**
2. **These languages are often *complex & unclearly defined and combined***
3. **The code handles all these languages & formats in sloppy way,**
   - **as the succes of fuzzing demonstrates**
   - **the prevalence of input attacks (path traversals, SQL injection, XSS, ...) shows**

Tower of Babel

A typical interaction on the web involves *__many__* languages & formats

HTTP(S), HTML5, CSS3, javascript, Flash, cookies & FSOs,

Ajax & XML, ActiveX, jpeg, mpeg, mp4, png, gif, SilverLight,

user names, email addresses, phone numbers,

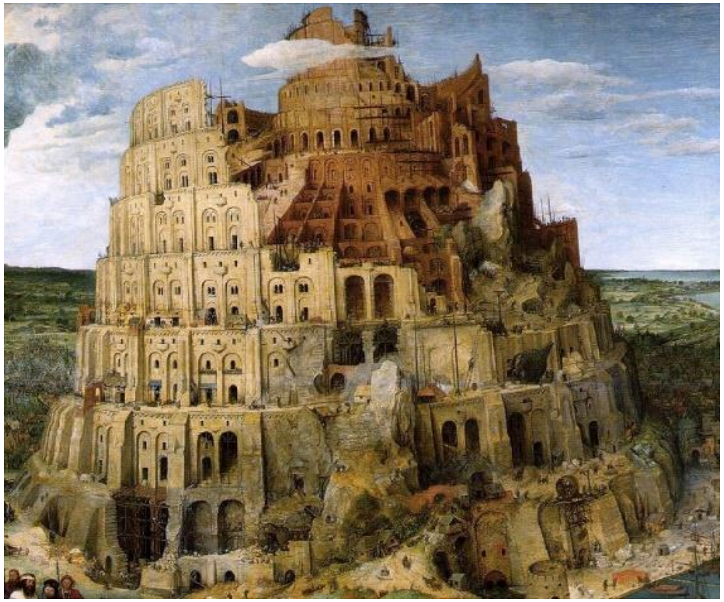
URLs, X509 certificates, TCP/IP (IPv4 or IPv6), DNS,

file names, directories, OS commands, SQL,

database commands, LDAP, JSP, PHP,

ASCII, Unicode, UTF-8, ...

Some handled by web application & browser,
some others by lower protocol layers or
by external programs & services



Input attacks on software

The common pattern in many attacks on software

> **buffer overflows, format string attacks, integer overflow, OS command injection, path traversal attacks, SQL injection, HTML injection, XSS, CSRF, database command injection, database function injection, PHP file name injection, LDAP injection, ..., ShellShock, HeartBleed,...**

is

1. **attacker crafts some *malicious input***
2. **software goes off the rails *processing* this:**
   - **Sometimes it simply crashes, and attacker can do DoS attack.**
   - **Sometimes, this exposes all sort of unintended functionality to attackers.**

Like social engineering or hypnosis as attack vector on humans?

Processing input

Processing involves

1) parsing/lexing

2) interpreting/executing

Eg *interpreting* a string as filename, URL, or email address,
or *executing* a piece of OS command, javascript, SQL statement

This relies on some language or format

Step 1) above relies on syntax of this language

Step 2) above relies also on semantics of this language

Processing input is dangerous!

Different ways for an attacker to abuse input

- ***wasting resources*** **(eg, a zip-bomb)**
- ***crashing things*** **(and causing DoS)**
- ***abusing strange functionality that is accidentily exposed***
  - **existing functionality of say SQL database or the OS, or more bizarre functionality exposed by say a buffer overflow attack,**
  - ***Insecure*** **processing of inputs provides a weird machine that the attacker can "program" to abuse the system**

Garbage In, Garbage Out (GIGO)

becomes

Malicious **Garbage In, Security Incident Out**

Fallacy of classical input validation?

Classical input validation:

filter or encode harmful characters

or, slightly better:

only let through harmless characters

But:

- Which characters are harmful (or required!) depends on the language or format. You need *context* to decide which characters are dangerous.
- Not only *presence* of funny characters can cause problems, but als the *absence* of other characters, or input fields that are too long or too short, ...

Sample problems (already mentioned earlier)

- Code Red worm exploiting difference in size (in bytes) between between `char`'s and Unicode charararacters
- Exploits with zero-width fields in JPEG images
- Malformed Flash files exploiting flaws in Abode's flashplayer
- All the GSM problems revealed with fuzzing (1 week ago)
- *Correctly formatted* NFC traffic crashing contactless payment terminals [MSc thesis Jordi van den Breekel, 2014]

Sample problems: Combining languages & formats

X509 certificates involve various languages & formats.
Differences in interpretation caused various security flaws:

- **ANS.1 attacks in X509 certificates**
  A null terminator in ANS.1 BER-encoded string in an `CommonName` can cause a CA to emit a certificate for an unauthorized Common Name.

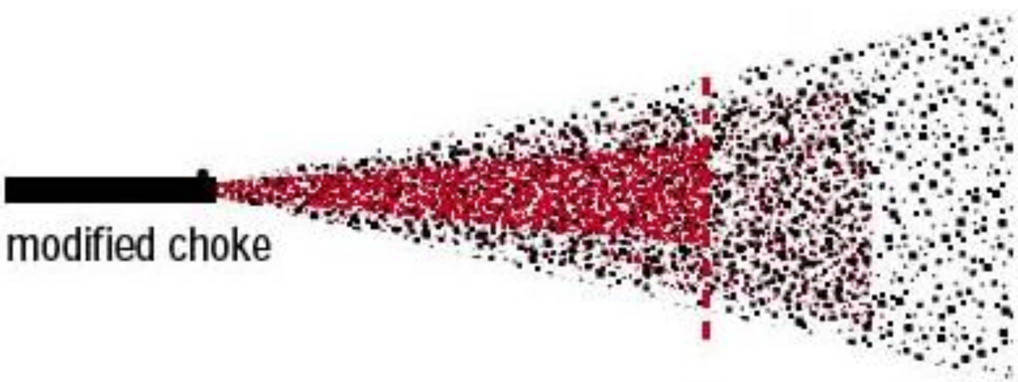
- **Multiple Common Names**
  allowed in X509, but handled diferently in different browsers

- **PKCS#10-tunneled SQL injection**
  SQL command *inside* a `BMPString`, `UTF8String` or `UniversalString` used as PKCS#10 `Subject Name`

[Dan Kaminsky, Meredith L. Patterson, and Len Sassaman,
PKI Layer Cake: New Collision Attacks Against the Global X.509 Infrastructure]

Anti-pattern 1: shotgun parsers

handwritten code that incrementally parses & interprets input, in a piecemeal fashion



An example shotgun parser

```
char buf1[MAX_SIZE], buf2[MAX_SIZE];
// make sure url is valid URL and fits in buf1 and buf2:
if (!isValid(url)) return;
if (strlen(url) > MAX_SIZE - 1) return;
// copy url up to first separator, ie. first '/', to buf1
out = buf1;
do { // skip spaces
   if (*url != ' ') *out++ = *url;
} while (*url++ != '/');
strcpy(buf2, buf1);
...
```

loop termination flaw (for URL without /) caused Blaster worm

[Code sample from presentation by Jon Pincus]

Anti-pattern 2: Strings considered harmful

- Strings can be used to represent all sorts of data:
  email addresses, URLs, fragments of SQL statements, fragments of HTML, HTML-escaped text, ...
  which may or may not be validated
  which may come from a trusted or untrusted source
- Some interfaces that take strings as input are very powerful
  eg `system()`, `executeUpdate()`, …
- Therefore: Strings are suspicious because they may hide many languages and associated processing power for an attacker to abuse
- Better to use more informative types
  - Recall the ideas behind Wyvern to make the different formats and languages more explicit in the programming language
  - To root out XSS flaws, modern web frameworks introduce more informative types to distinguish data that is (un)trusted and/or escaped for a particular context
    - eg SafeURL, SafeHTML, TrustedResourceURL

      [Christoph Kern, Securing the Tangled Web, ACM Queue 2014]

Root causes/Anti-patterns

Obstacles in producing code without input vulnerabilities

1. **ad-hoc and imprecise notion of input validity**
2. **parser differentials**

   eg web-browsers parsing X509 certificates in different ways

3. **mixing input recognition & processing**

   aka shotgun parsers

4. **unchecked development of input languages**

   ie always adding new features & continuously evolving standards

All this results in weird machines, ie. systems that an attacker can "program" with malicious input

LangSec principles

No more hand-coded shotgun parsers, but

1. *precisely defined* input languages

   eg with EBNF grammar

2. *generated* parser

3. *complete parsing before processing*

   So don't substitute strings & then parse,

   but parse & then substitute in parse tree

   (eg parameterised query instead of dynamic SQL)

4. *keep the input language simple & clear*

   So that equivalence of parsers is ideally decidable

   So that you give minimal processing power to attackers


FULL RECOGNITION
BEFORE PROCESSING

Weird machine = the strange functionality accidentality exposed by code that (incorrectly) processing input

Attackers can program this weird machine with their malicious input!

Minimise the resources & computing power that input handling gives to attackers .


NO MORE
Turing-
Complete
Input
Languages

Turing completeness

Two ways in which Turing completeness may cause problems

1. **An input language may be Turing complete in the sense that an attacker can perform arbitrary computations**

2. **Deciding if two acceptors accept the same language can be an undecidable problem – ie Turing complete**

If input languages are *context-free* or *regular*, then equivalence of acceptors is decidable.

No more length fields?

Proponents of LangSec argue against using length fields in data formats

- **Length fields are a common source of trouble**
  - **incorrect length fields often cause buffer overflows**
- **They also make acceptor equivalence undecidable**
  - **because the resulting language is no longer regular or context-free**


COMPUTATIONAL
EQUIVALENCE
FOR ALL
PROTOCOL
ENDPOINTS

NB possible confusion in terminology

- Language-*based* security

  Providing safety/security features at programming language level

  Eg memory-safety, type-safety, thread-safety, sandboxing,…

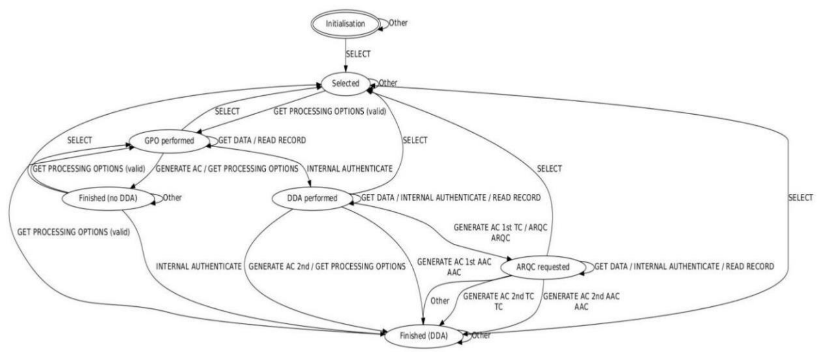
  Making programming less error-prone

  Here language = *programming* language

- Language-*theoretic* security (LangSec)

  Making handling input less error-prone

  Here language = *input* language



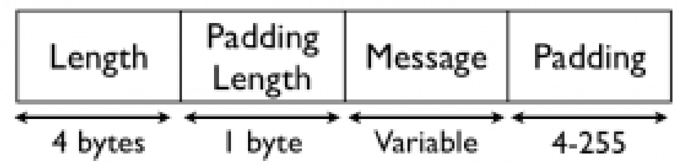
State Machine Learning

(yet another from of fuzzing)

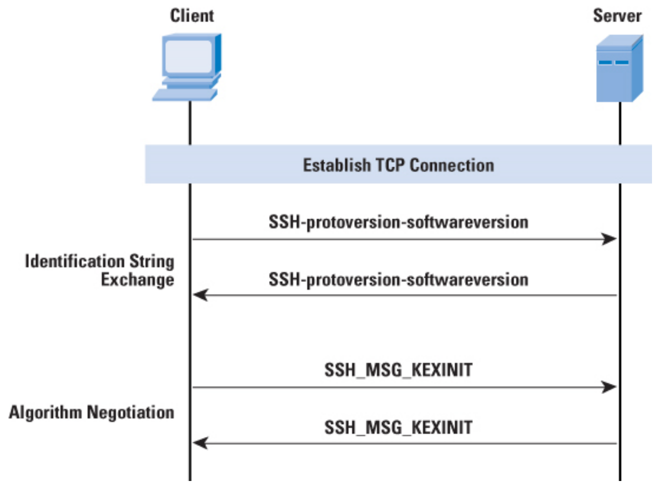
Protocols

Many procotols involve two levels of languages

1) a language of input messages or packets



2) a notion of session, or *sequence* of messages



How can we test or fuzz these two levels?

For level 1 we can use fuzzing techniques discussed last week

For level 2 we can do something different, as we discuss now.

Message Sequence Charts (MSCs)

1. $C \rightarrow S$: CONNECT
2. $S \rightarrow C$: VERSION_S server version string
3. $C \rightarrow S$: VERSION_C client version string

} protocol identification

4. $S \rightarrow C$: SSH_MSG_KEXINIT I_C
5. $C \rightarrow S$: SSH_MSG_KEXINIT I_S

} key exchange algorithm negotiation

6. $C \rightarrow S$: SSH_MSG_KEXDH_INITe
   where $e = g^x$ for some client nonce x
7. $S \rightarrow C$: SSH_MSG_KEXDH_REPLY$K_S, f, sign_{K_S}(H)$
   where $f = g^y$ for some server nonce y,
   $K = e^y$ and $H = hash(V_C, V_S, I_C, I_S, K_S, e, f, K)$,
   K_S is the server key
8. $S \rightarrow C$: SSH_MSG_NEWKEYS
9. $C \rightarrow S$: SSH_MSG_NEWKEYS

} key exchange

10. …

} session, incl. SSH authentication and connection protocols

Typical spec given as Message Sequence Chart or in Alice-Bob style.

NB this *oversimplifies* because it only specifies *one correct run*, *the so-called happy flow*

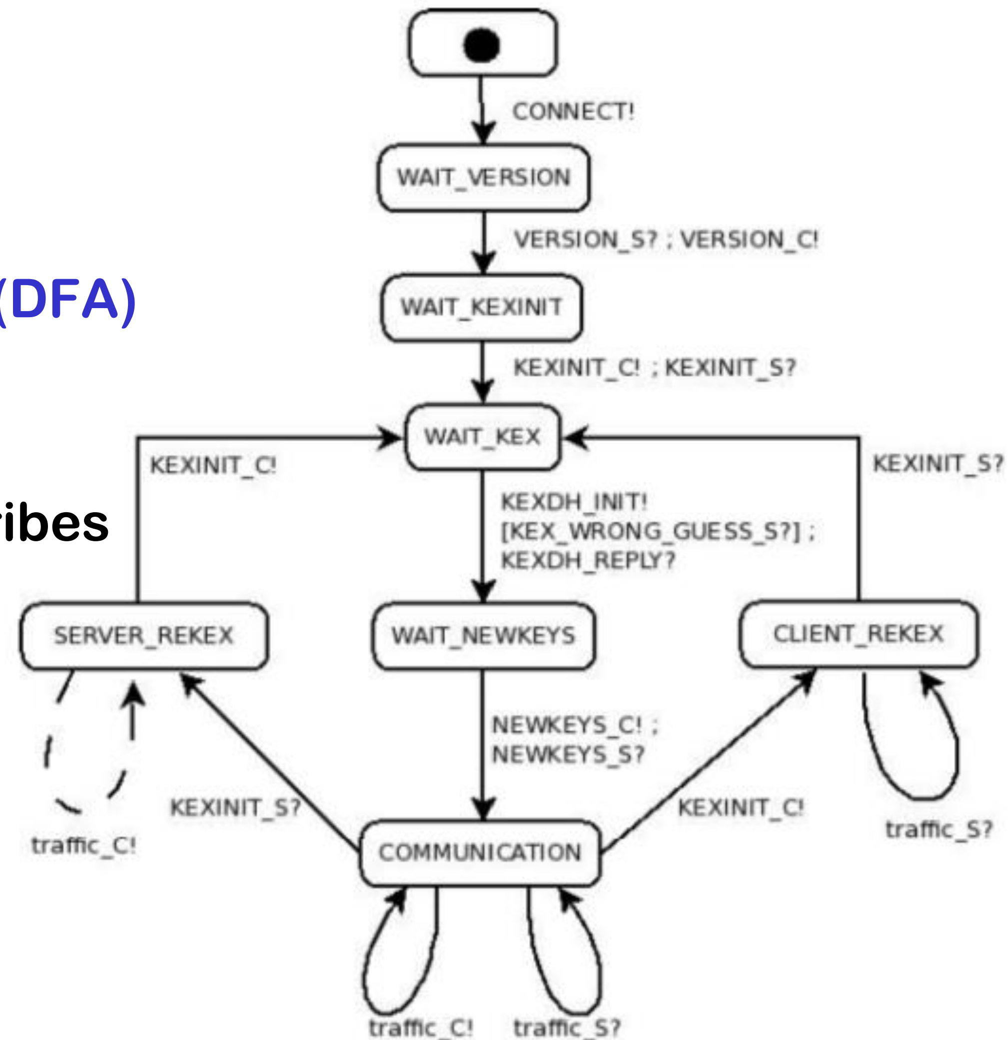
protocol state machines

A protocol is typically more complicated than a simple sequential flow.

A better spec can be given using a Finite State Machine (FSM) aka Deterministic Finite Automaton (DFA)

This still oversimplifies: it only describes happy flows, albeit several ones.

The implementation will have to be input-enabled



SSH transport layer

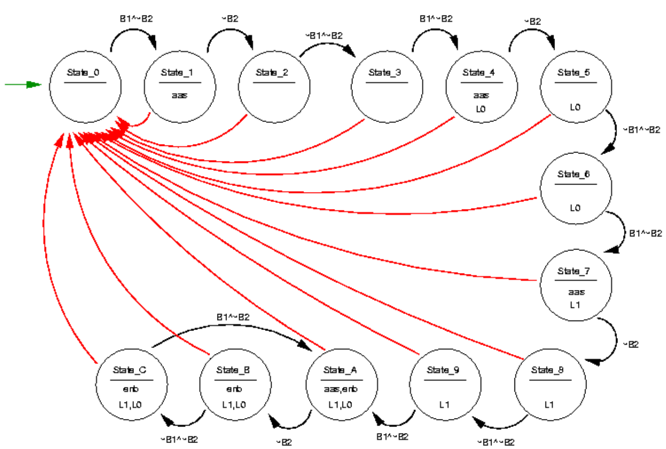
input enabled state machines

A state machine is input enabled iff

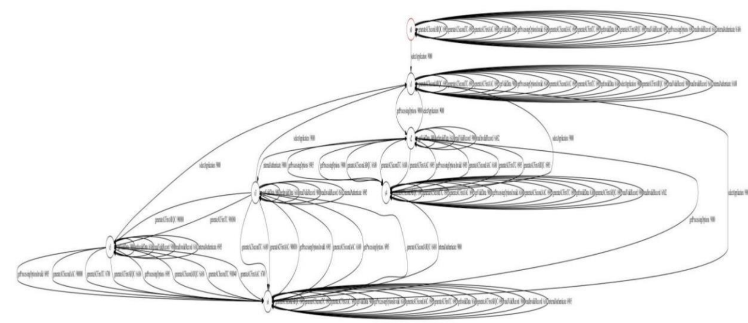
in *every* state

it is able to receive *every* message

Often, many messages go to 1) some error state, 2) back to the initial state, or 3) are ignored



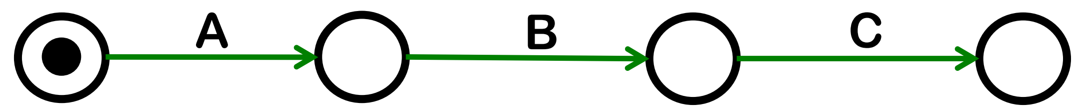
2)



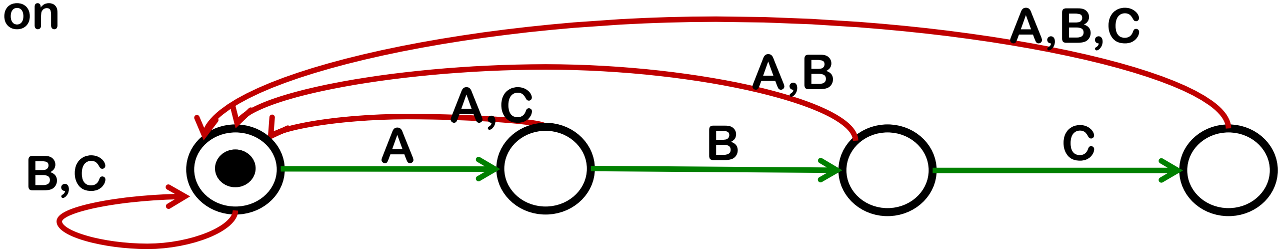
3)

input enabling

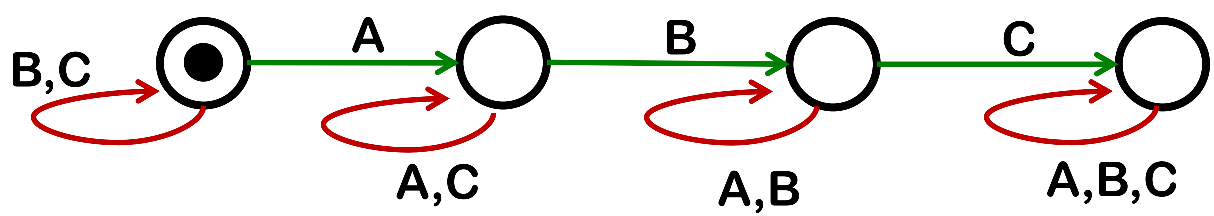
State machine that is not input-enabled



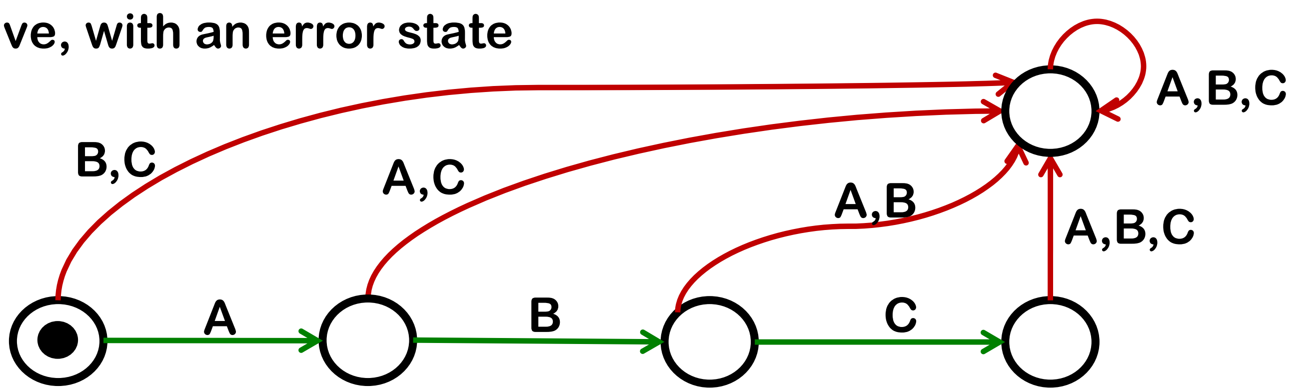
Input enabled version



Alternative input enabled version



Yet another alternative, with an error state



Typical prose specifications: SSH ☹

“Once a party has sent a SSH_MSG_KEXINIT message for key exchange or re-exchange, until it has sent a SSH_MSG_NEWKEYS message, it MUST NOT send any messages other than:

- Transport layer generic messages (1 to 19) (but SSH_MSG_ SERVICE REQUEST and SSH_MSG_SERVICE_ACCEPT MUST NOT be sent);
- Algorithm negotiation messages (20 to 29) (but further SSH_MSG KEXINIT messages MUST NOT be sent);
- Specific key exchange method messages (30 to 49).

The provisions of Section 11 apply to unrecognised messages”

In Section 11:

> “An implementation MUST respond to all unrecognised messages with an SSH_MSG_UNIMPLEMENTED. Such messages MUST be otherwise ignored. Later protocol versions may define other meanings for these message types.”

Understanding protocol state machine from prose is hard!

Typical prose specifications: EMV ☹☹

Excerpt of the EMV contactless specs

“If the card responds to GPO with SW1 SW2 = x9000 and AIP byte 2 bit 8 set to b0, and if the reader supports qVSDC and contactless VSDC, then if the Application Cryptogram (Tag '9F26') is present in the GPO response, then the reader shall process the transaction as qVSDC, and if Tag '9F26' is not present, then the reader shall process the transaction as VSDC.”

Example security flaws due to broken state machines

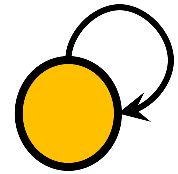
CVE-2018-10933 libssh

- **libssh versions 0.6 and above have an authentication bypass vulnerability in the server code. By presenting the server an SSH2_MSG_USERAUTH_*SUCCESS* message in place of the SSH2_MSG_USERAUTH_*REQUEST* message which the server would expect to initiate authentication, the attacker could successfully authentciate without any credentials.**

https://www.libssh.org/security/advisories/CVE-2018-10933.txt

Example security flaws due to broken state machines

- **MIDPSSH**

  no state machine implemented at all 

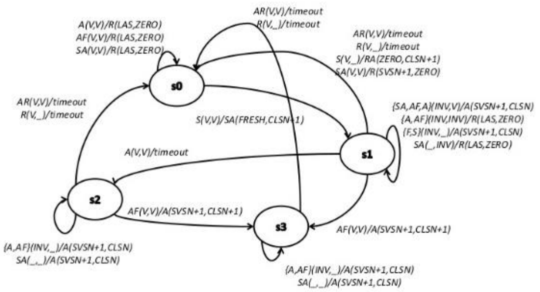
  [Verifying an implementation of SSH, WIST 2007]

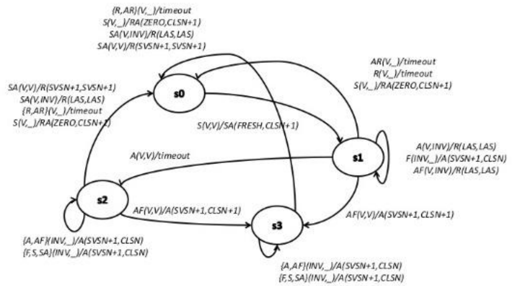
- **e.dentifier2**

  strange sequence of USB commands by-passes OK

  [Designed to fail: a USB-connected reader for online banking , NordSec 2012

There can also be fingerprinting possibilities due to differences in implemented protocol state machines, eg in e-passports from different countries or in TCP implementations on Windows/Linux





Extracting protocol state machines from code

We can infer a finite state machine from implementation by black box testing using state machine inference

- using L* algorithm, as implemented in eg. LearnLib

This is effectively a form of 'stateful' fuzzing using a test harness that sends typical protocol messages.

It can also be regarded as a form of automated reverse engineering

This is a great way to obtain protocol state machine

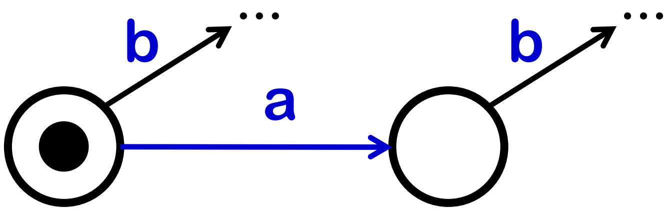
- without reading specs!
- without reading code!

State machine inference with L*

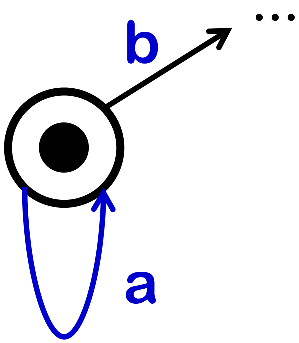
Basic idea: compare the response of a deterministic system to different input sequences, eg.

1. **b**
2. **a ; b**

If response is different, then



otherwise



The state machine inferred is only an *approximation* of the system, and only *as good as your set of test messages*.

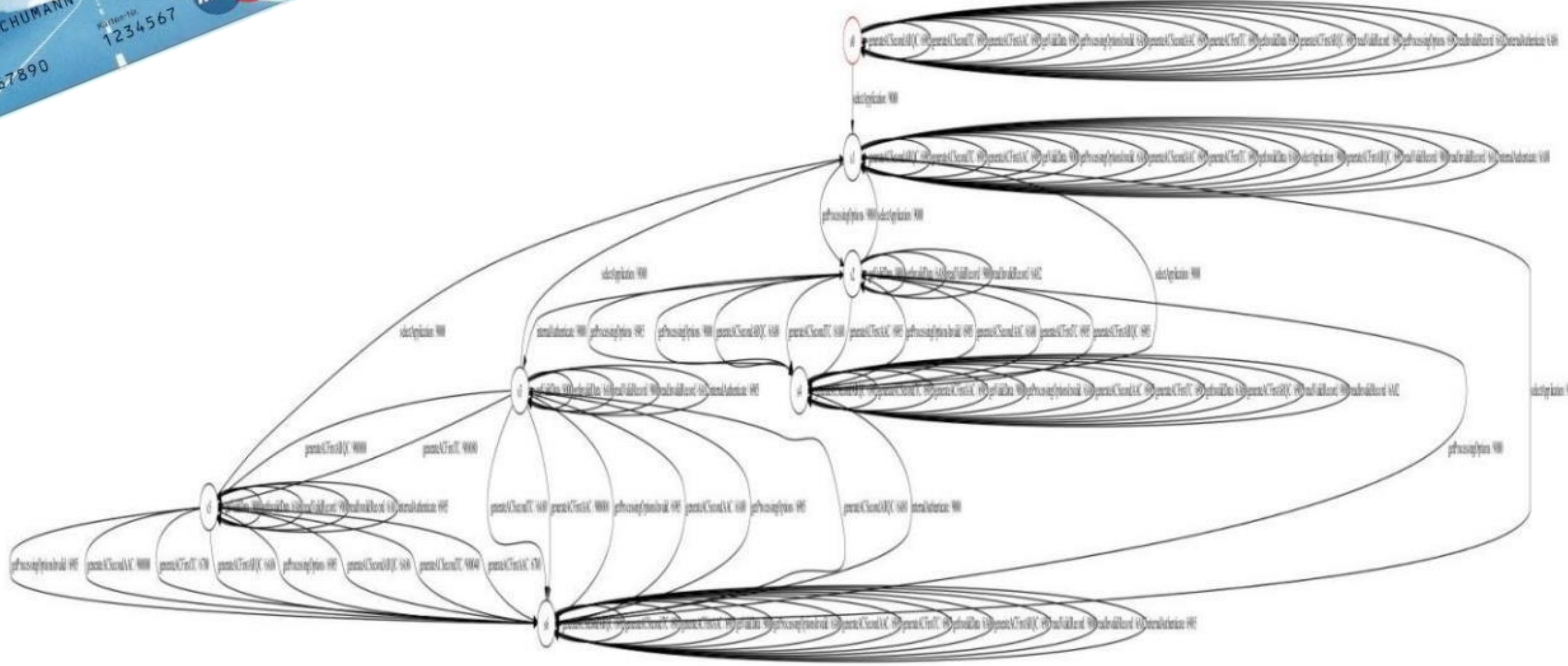
Case study 1: EMV

- **Most banking smartcards implement a variant of EMV**
- **EMV (Europay-Mastercard-Visa) defines set of protocols**

  with *lots* of variants

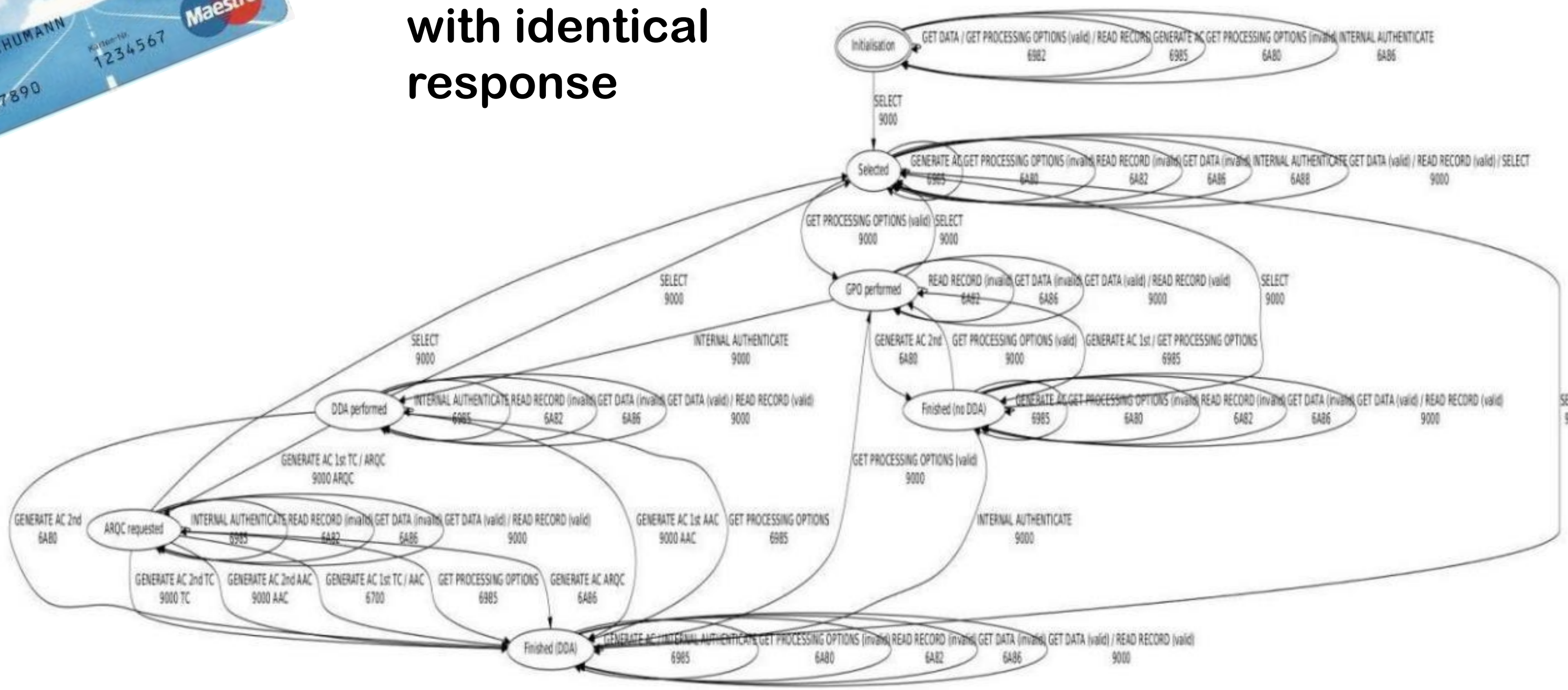
- **Specification in 4 books totalling > 700 pages**
- **EMV contactless specs: 10 more books, > 1500 pages**

State machine inference of Maestro card

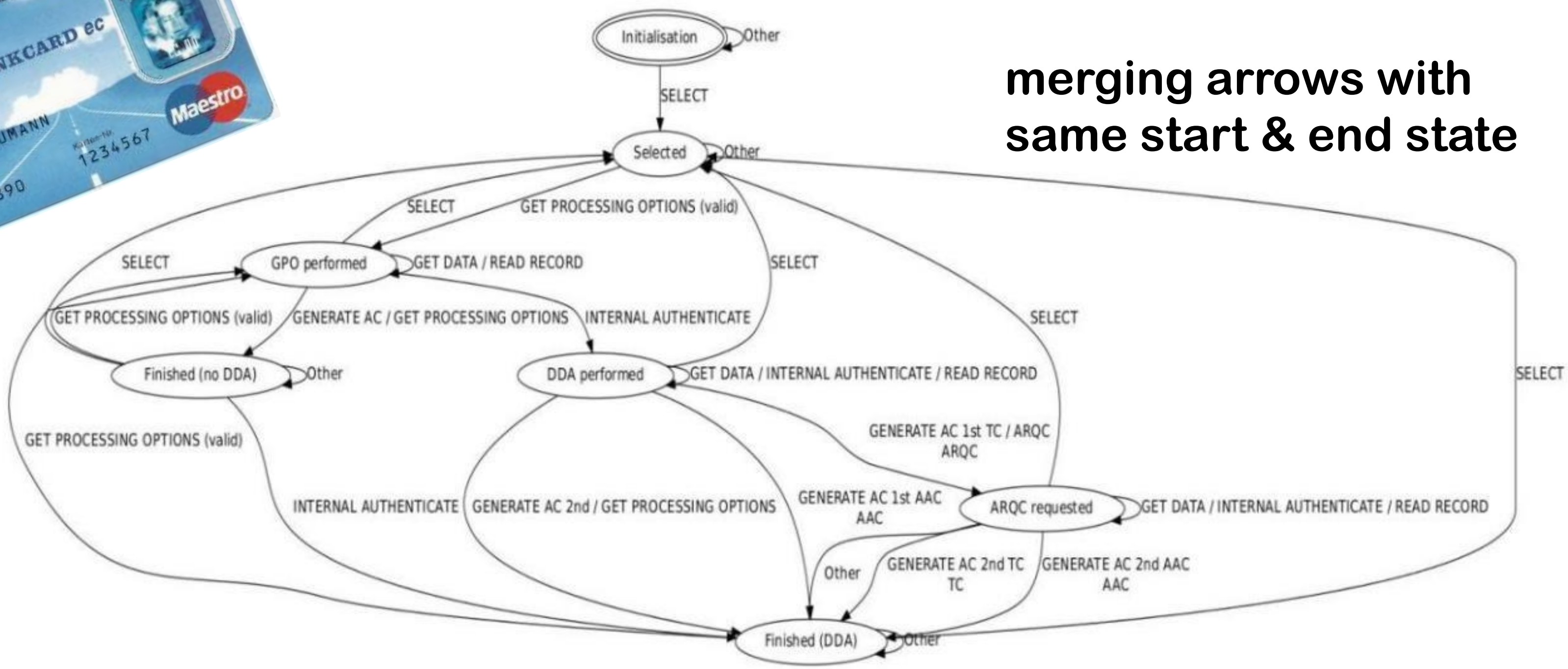


State machine inference of Maestro card

merging arrows
with identical
response



State machine inference of Maestro card



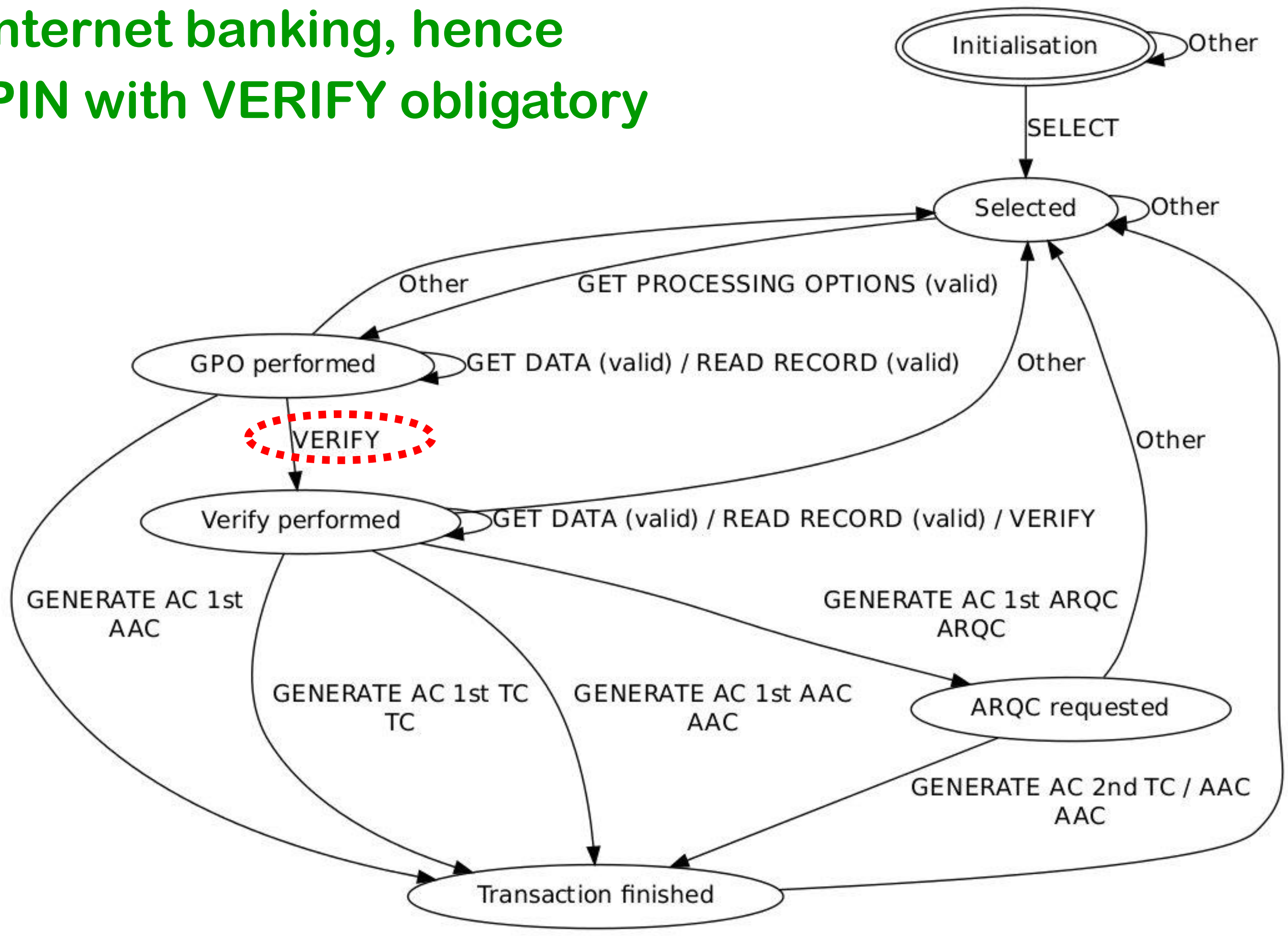
merging arrows with
same start & end state

We found no bugs, but lots of variety between cards.

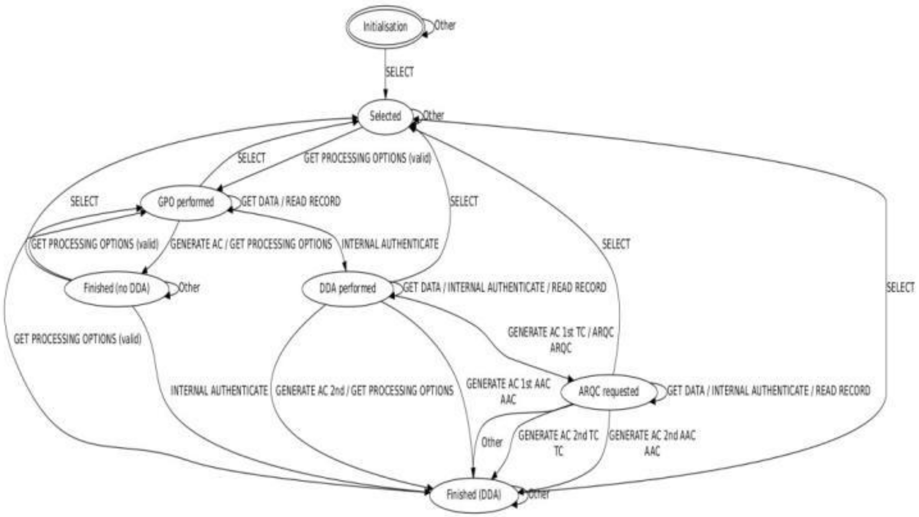
[Fides Aarts et al., Formal models of bank cards for free, SECTEST 2013]

SecureCode application on Rabobank card

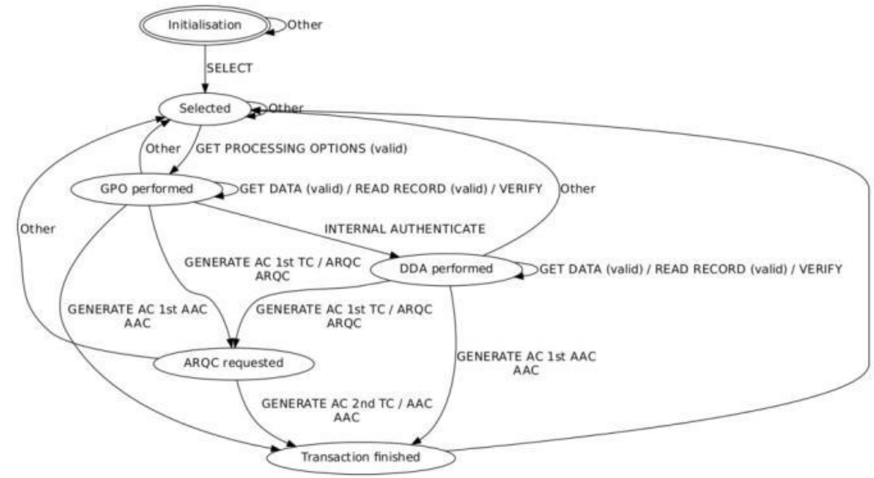
used for internet banking, hence entering PIN with VERIFY obligatory



Understanding & comparing EMV implementations



Volksbank Maestro implementation



Rabobank Maestro implementation

Are both implementations correct & secure? And compatible?

Presumably they both pass a Maestro compliance test-suite...

So some paths (and maybe some states) are superfluous?

Using such protocol state diagrams

- Analysing the models by hand, or with model checker, for flaws
  - to see if *all paths* are correct & secure
- Fuzzing or model-based testing
  - using the diagram as basis for “deeper” fuzz testing
    - eg fuzzing also parameters of commands
- Program verification
  - *proving* that there is no functionality beyond that in the diagram, which using just testing you can never be sure of
- Using it when doing a manual code review

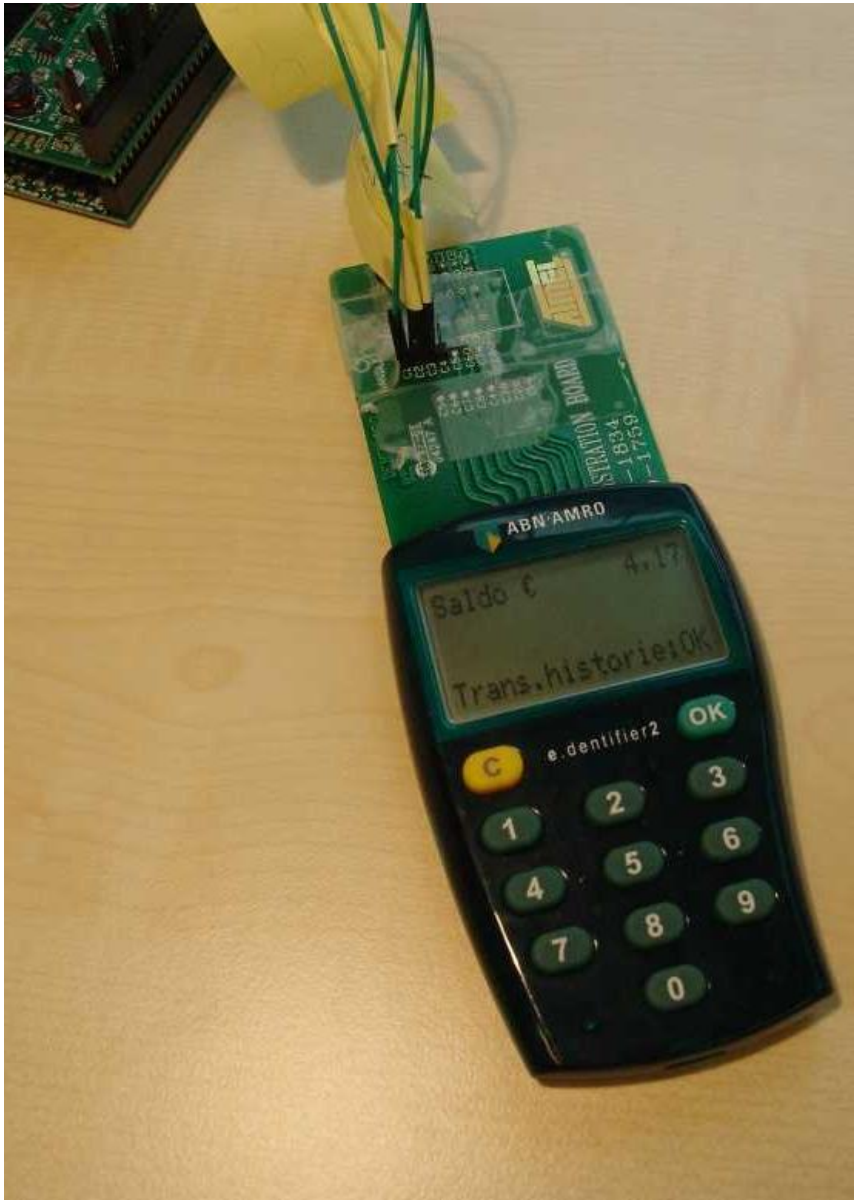
Case study 2: the USB-connected e.dentifier

Can we fuzz

- USB commands
- user actions via keyboard

to automatically reverse engineer

the ABN-AMRO e.dentifier2?

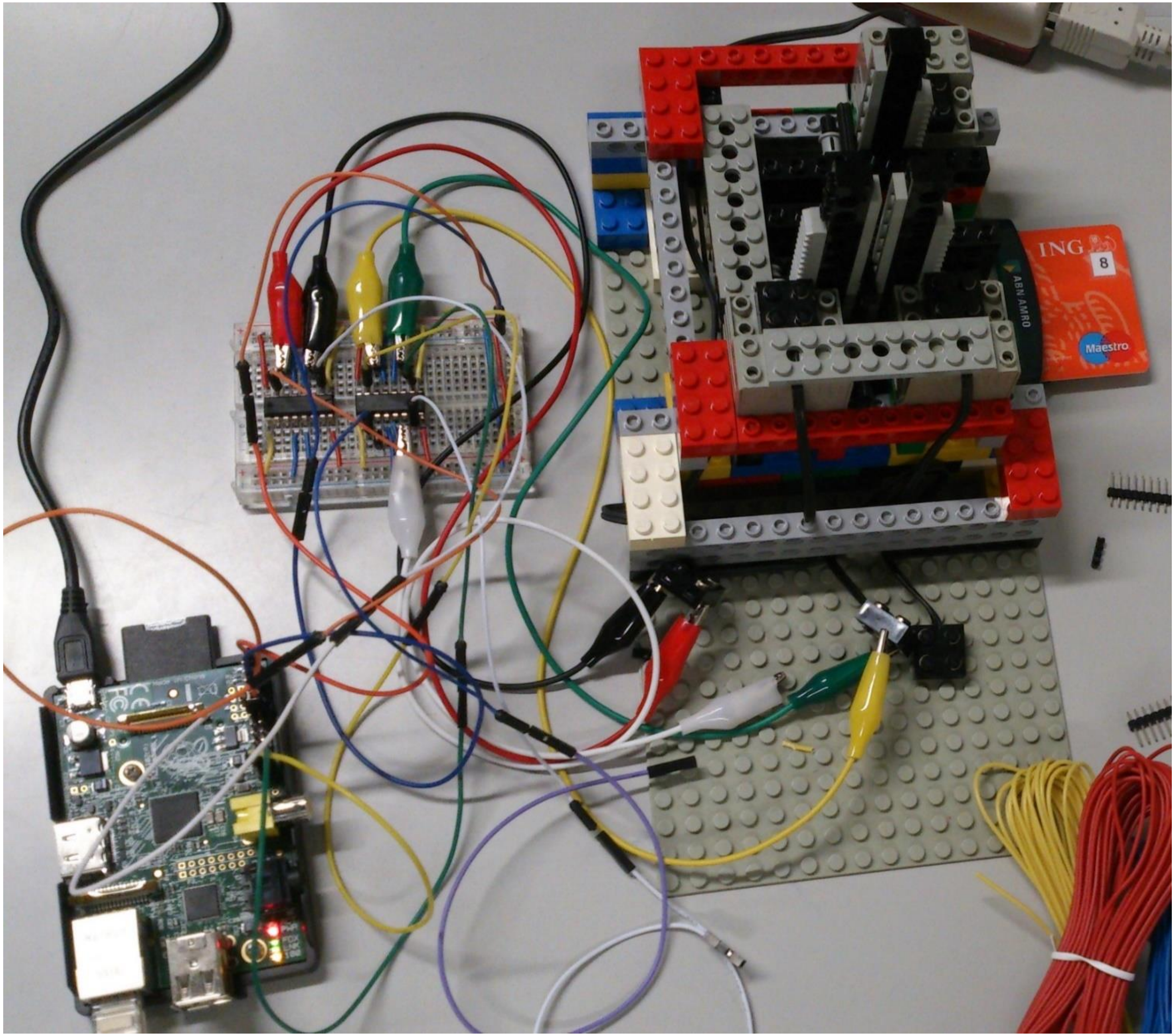


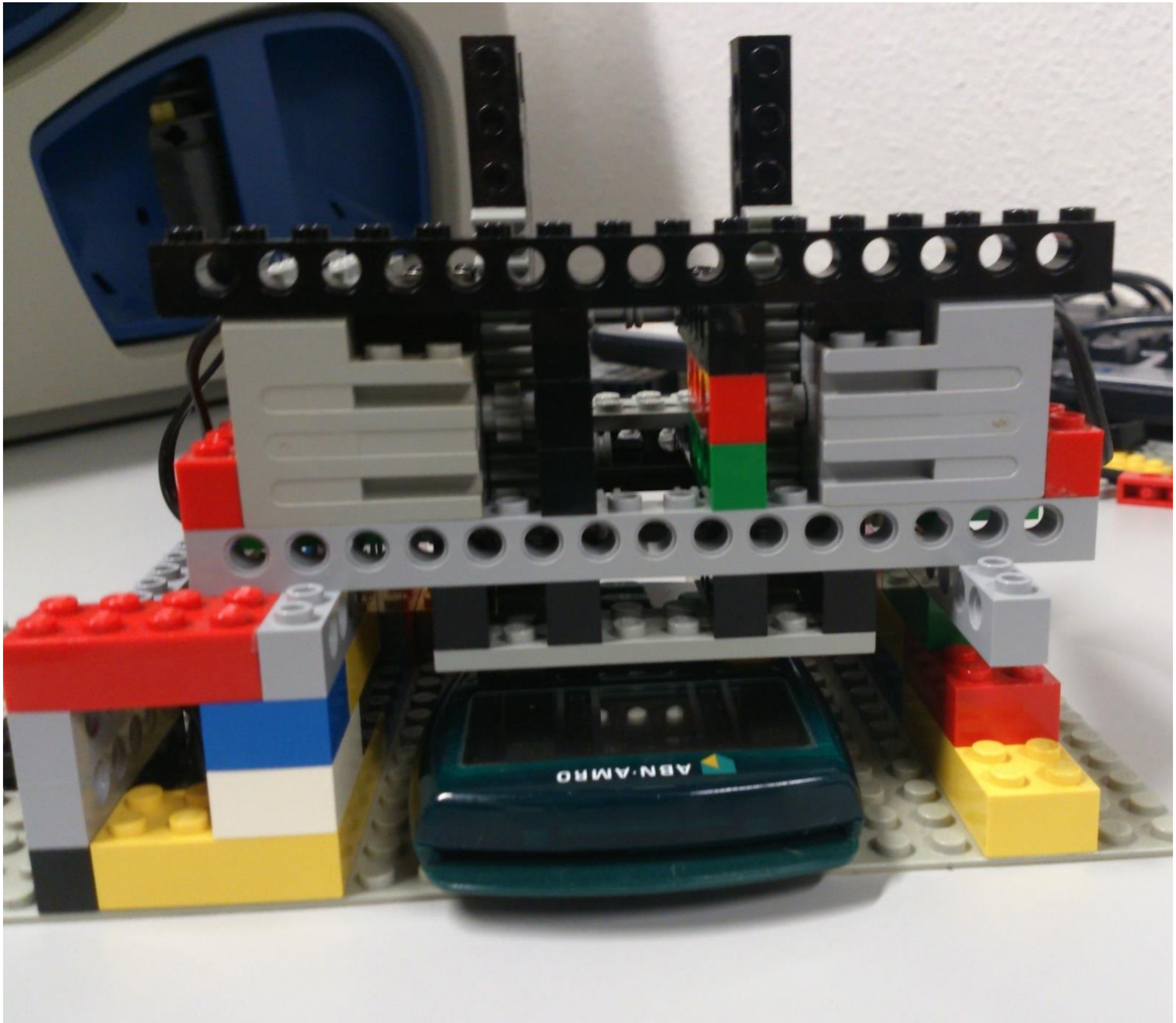
[Arjan Blom et al,

Designed to Fail: a USB-connected reader

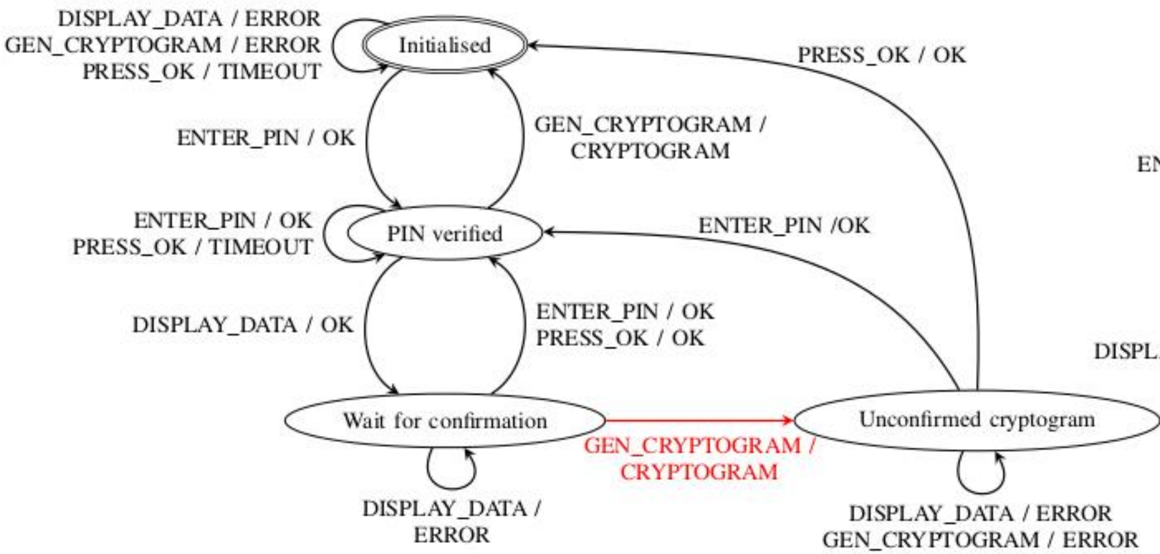
for online banking, NORDSEC 2012]

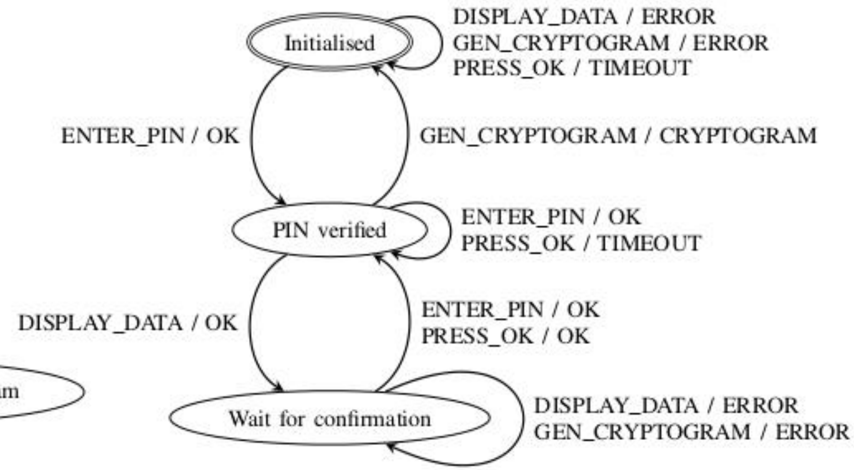
Operating the keyboard using

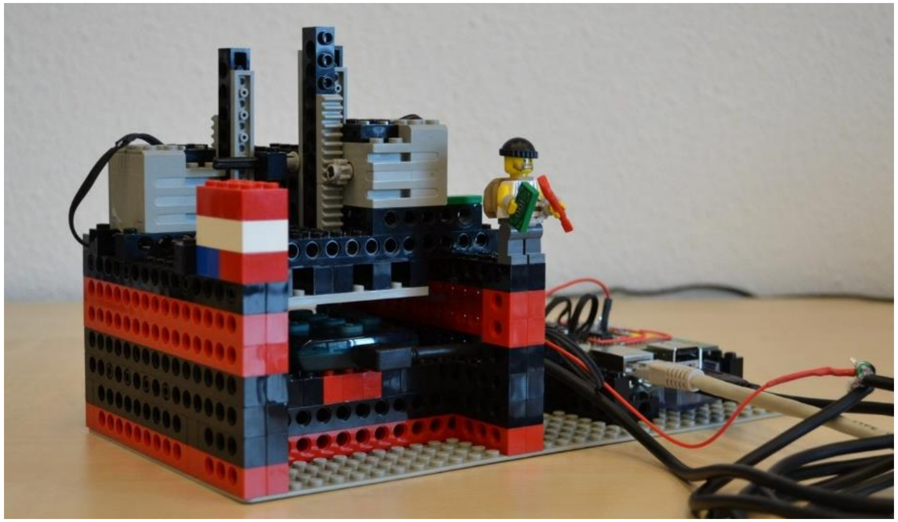

ING
8
ABN AMRO
Maestro


ABN·AMRO

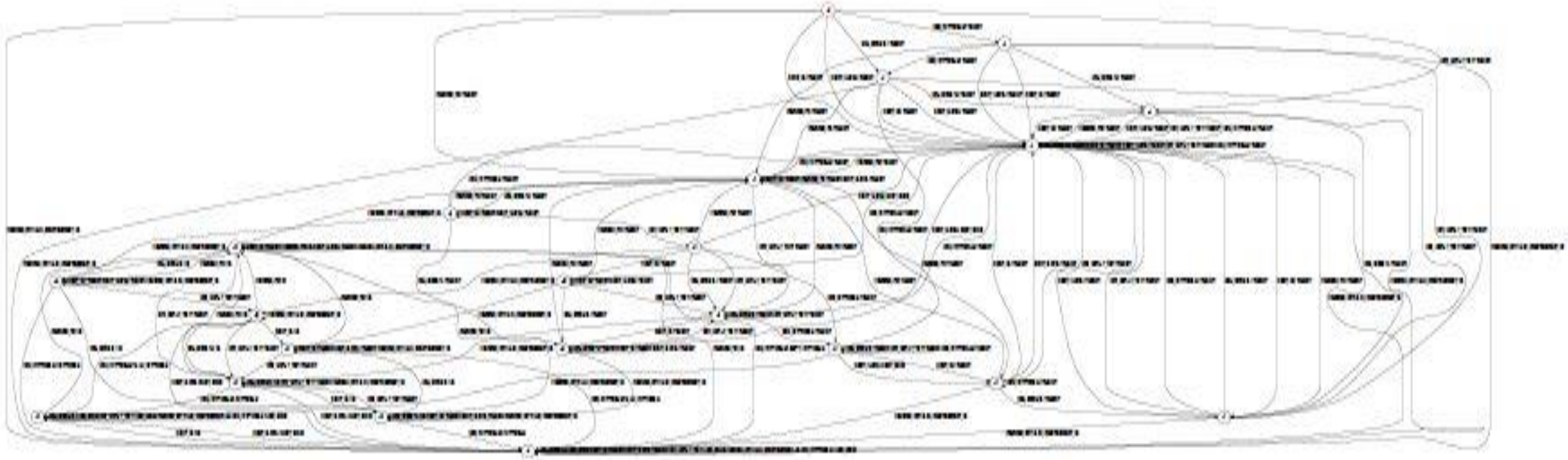
State machines of old vs new e.dentifier2







Would you trust this to be secure?



More detailed inferred state machine, using richer input alphabet.

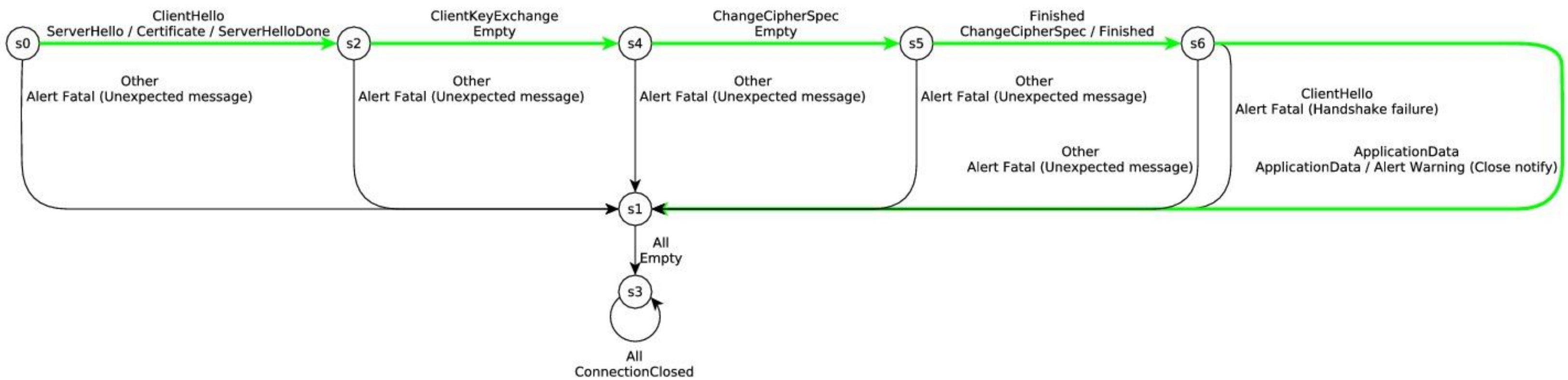
Do you think whoever designed or implemented this is confident that this is secure?
Or that all this behaviour is necessary?

Results with learning state machines for e.dentifier2

- Coarse models, with a limited alphabet, can be learnt in a few hours
  - these models are detailed enough to show presence of the known security flaw in the old e.dentifier, and absence of this flaw in the new one
- The most detailed models required 8 hours or more
- The complexity of the more detailed models suggest there was no clear protocol design that was used as the basis for the implementation

[Georg Chalupar et al., Automated Reverse Engineering using Lego, WOOT 2014]

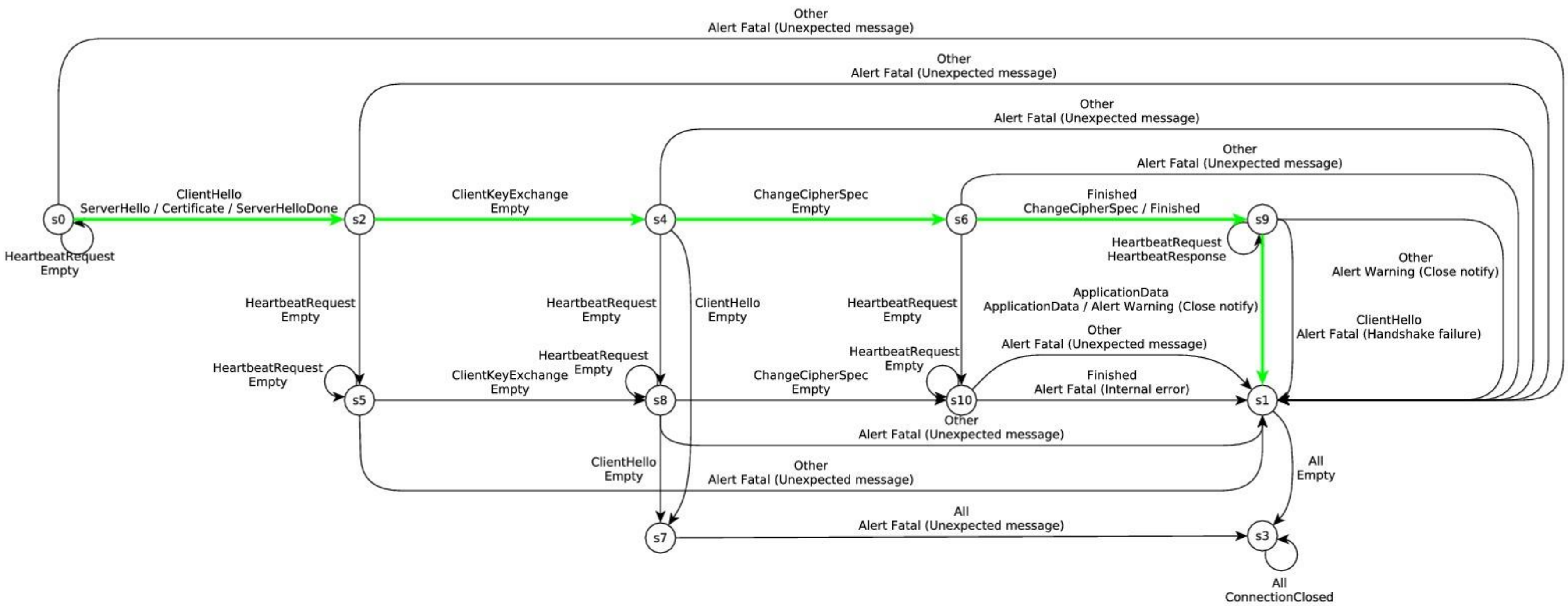
Case study 3: TLS



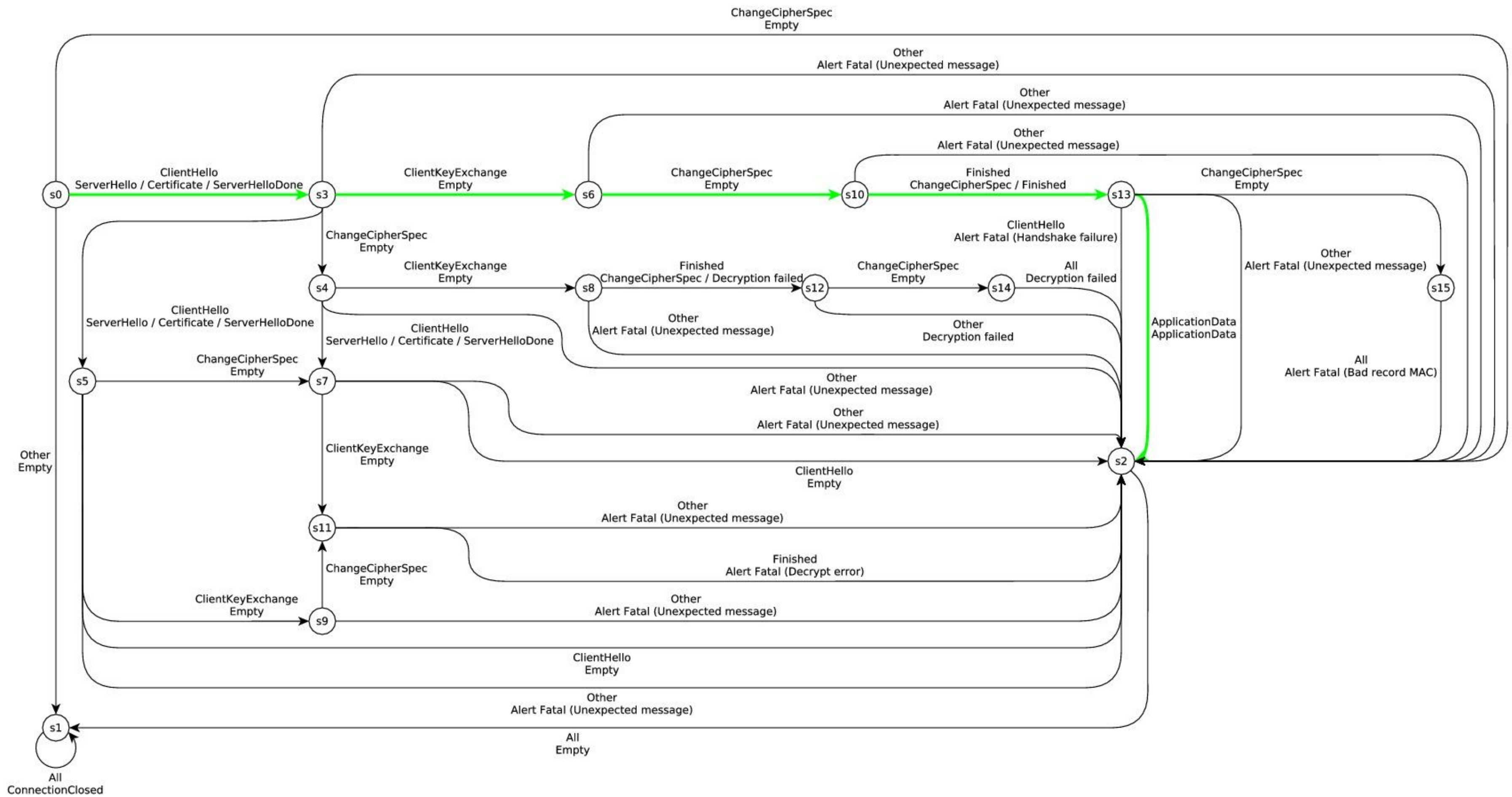
State machine inferred from NSS implementation

Comforting to see this is so simple!

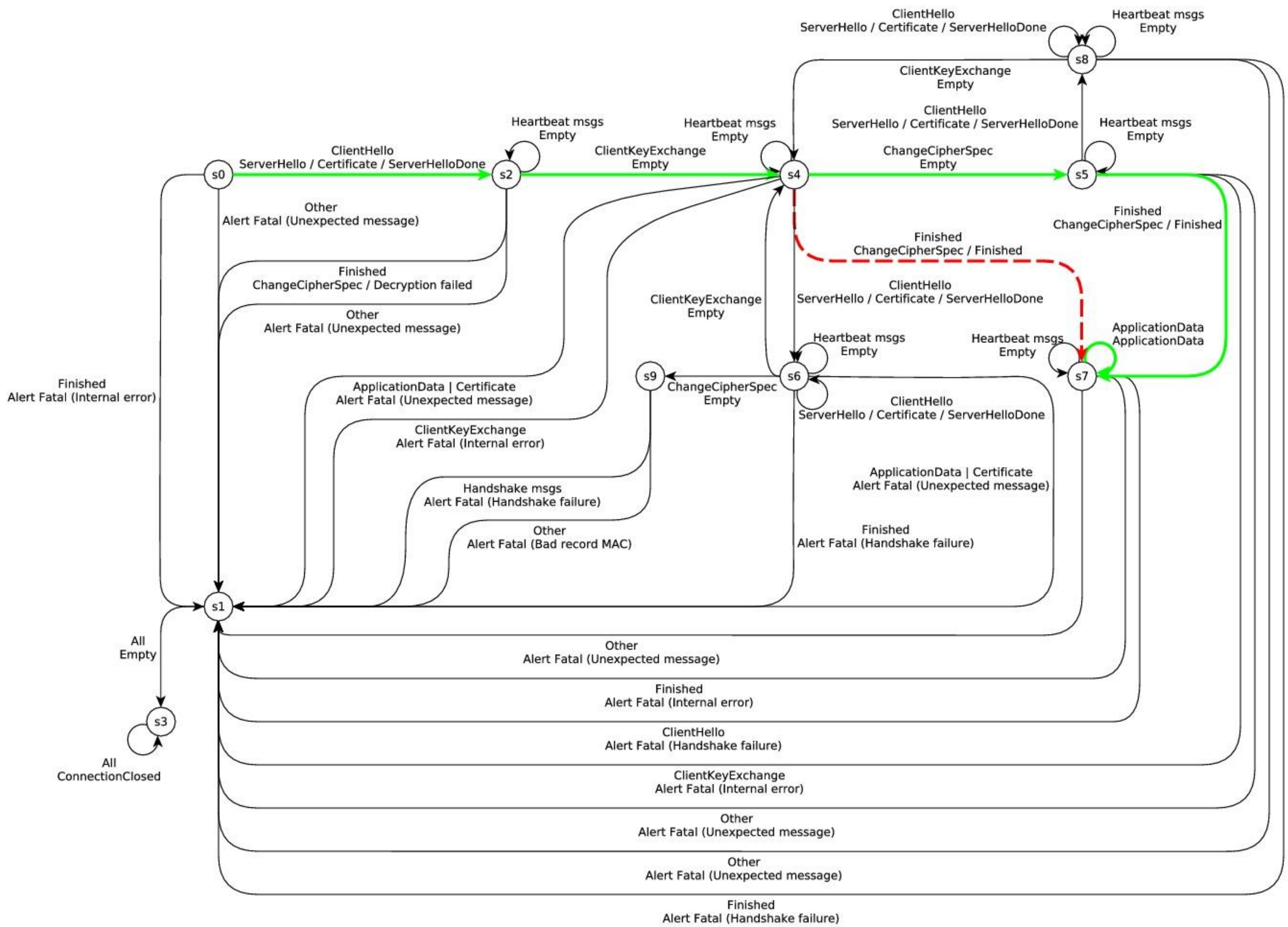
TLS... according to GnuTLS



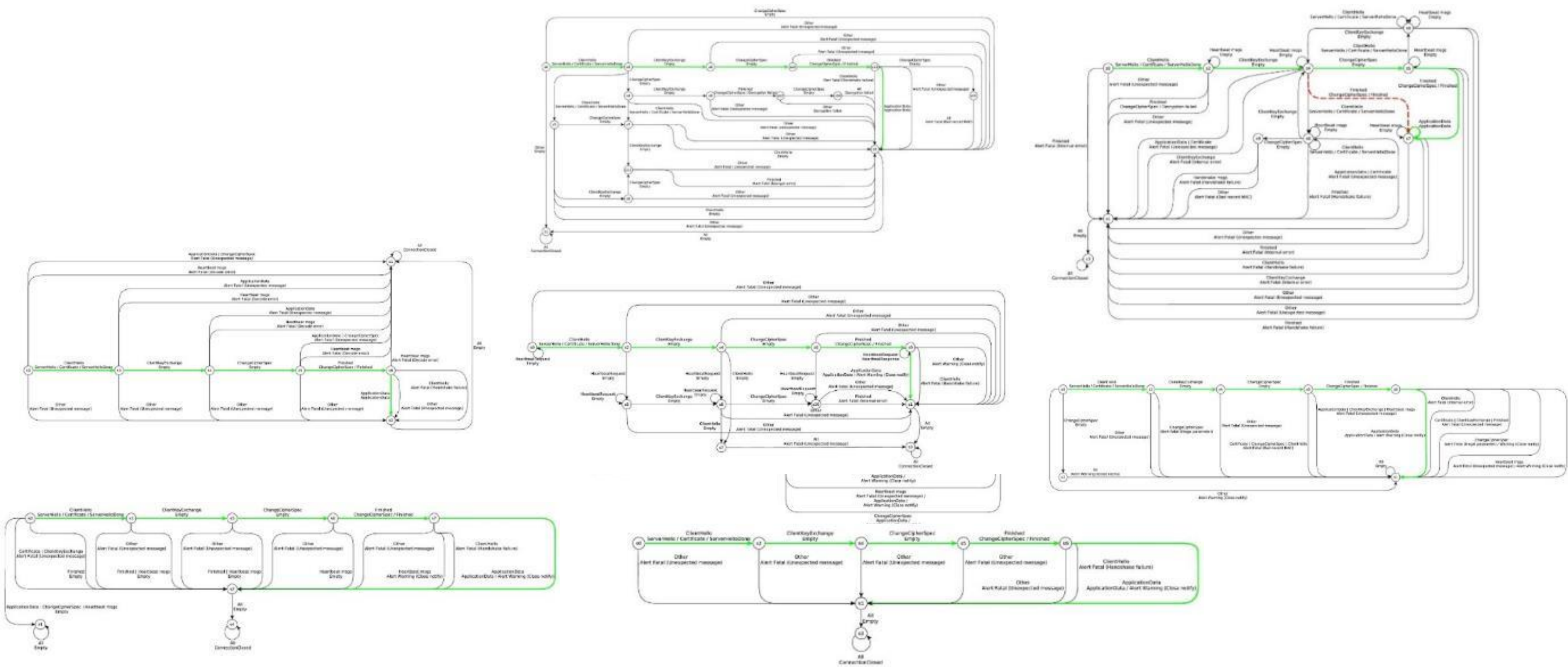
TLS... according to OpenSSL



TLS... according to Java Secure Socket Exension



Which TLS implementations are correct? or secure?



[Joeri de Ruiter et al., Protocol state fuzzing of TLS implementations, Usenix Security 2015]

Results with learning state machines for TLS

- Three new security flaws found, in
  - OpenSSL
  - GnuTLS
  - Java Secure Socket Extension (JSSE)
- One (not security-critical) flaw found in newly proposed reference implementation nqbs-TLS
- For most TLS implementations, models can be learned within 1 hour

Conclusions

Rigorous & clear specs using protocol state machines can improve security:

- **by avoiding ambiguities**
- **useful for programmer**
- **useful for model-based testing**

Open question: How common is this category of security flaws due to sloppy implementation of state machines?

In the absence of state machines in specs, extracting state machines from code using state machine inference is great for

- **security testing & analysis of implementations**
- **obtaining reference state machines for legacy systems**
  - **without having to read nasty RFCs or other specs**

To read

- **LangSec revisited: input security flaws of the second kind, LangSec18**

- **Protocol state machines and session languages: specification, implementation, and security flaws
LangSec'15**

specs

implementing

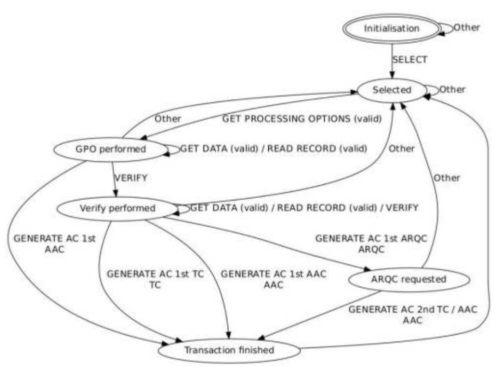
code

model-based

testing

state machine

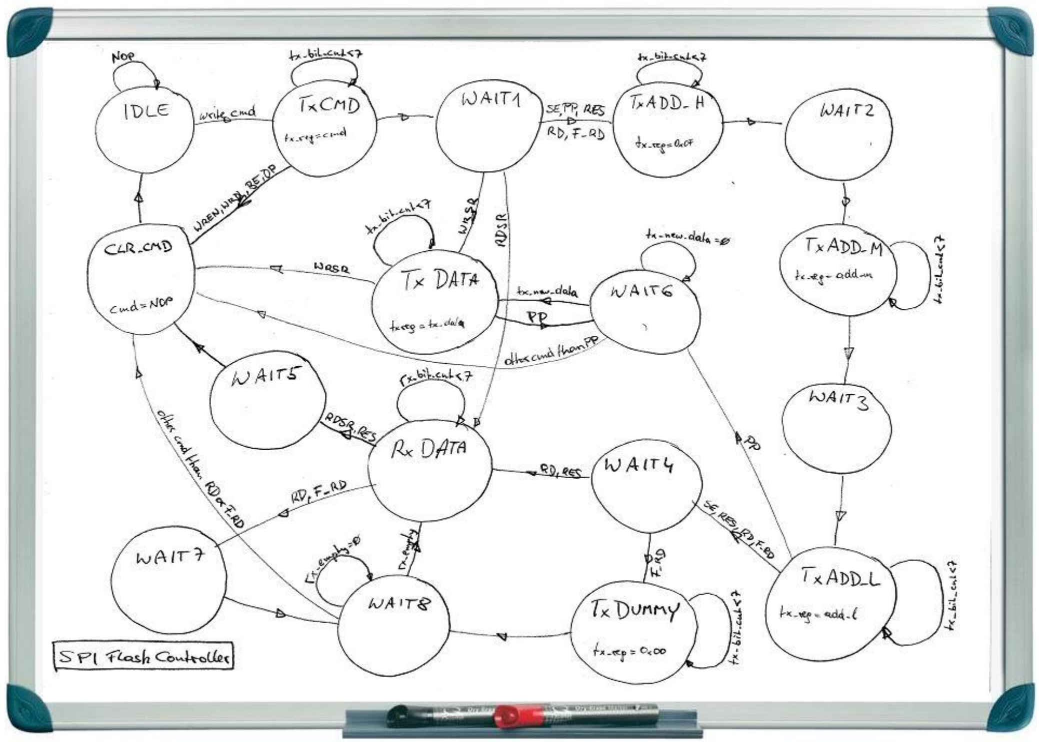
inference



model

The people who write specs, make implementations, or do security analyses probably all draw state machines on their whiteboards…

But will it they all draw an identical ones?




NO MORE PROSE
SPECIFICATIONS
OF PROTOCOL
STATE MACHINES