Model Checking Cryptoprocessors
(or "Why I Like the British Museum")

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Contents

- The Problem : Analysing Security APIs
- Protocol Analysis Tools
- The Formalisation Step
- Experiments with SPASS
- The “MIMSEARCH” Tool
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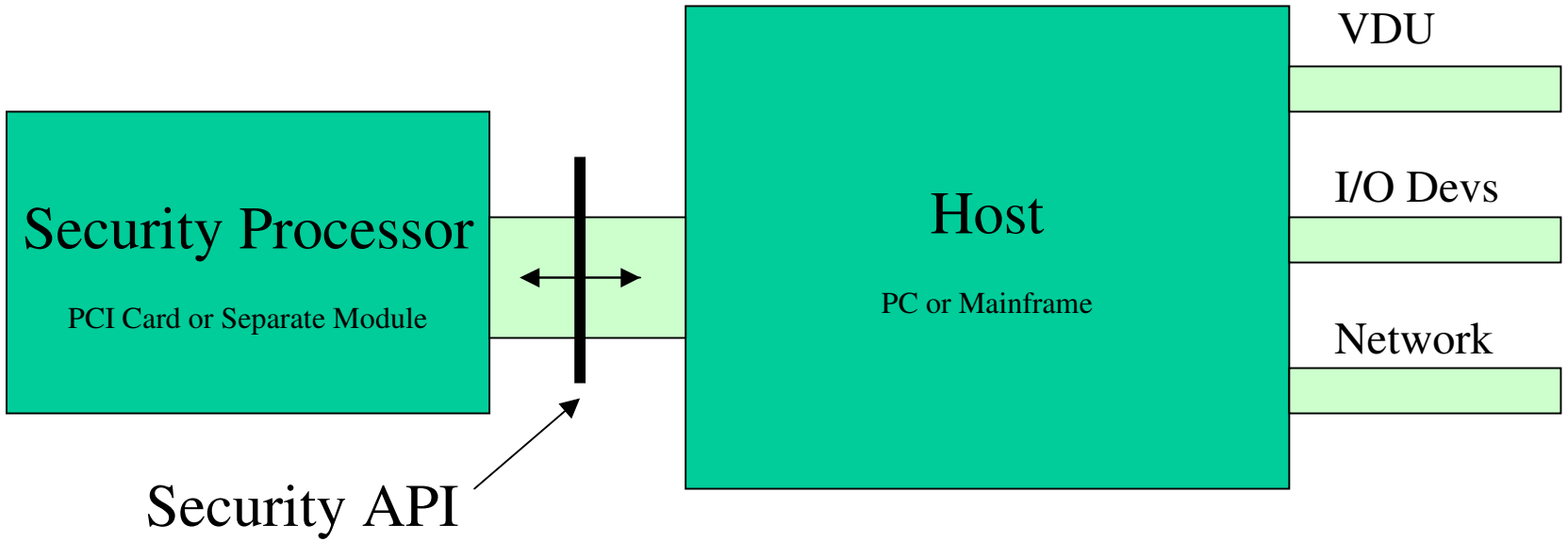
What is a Security API?

Security APIs

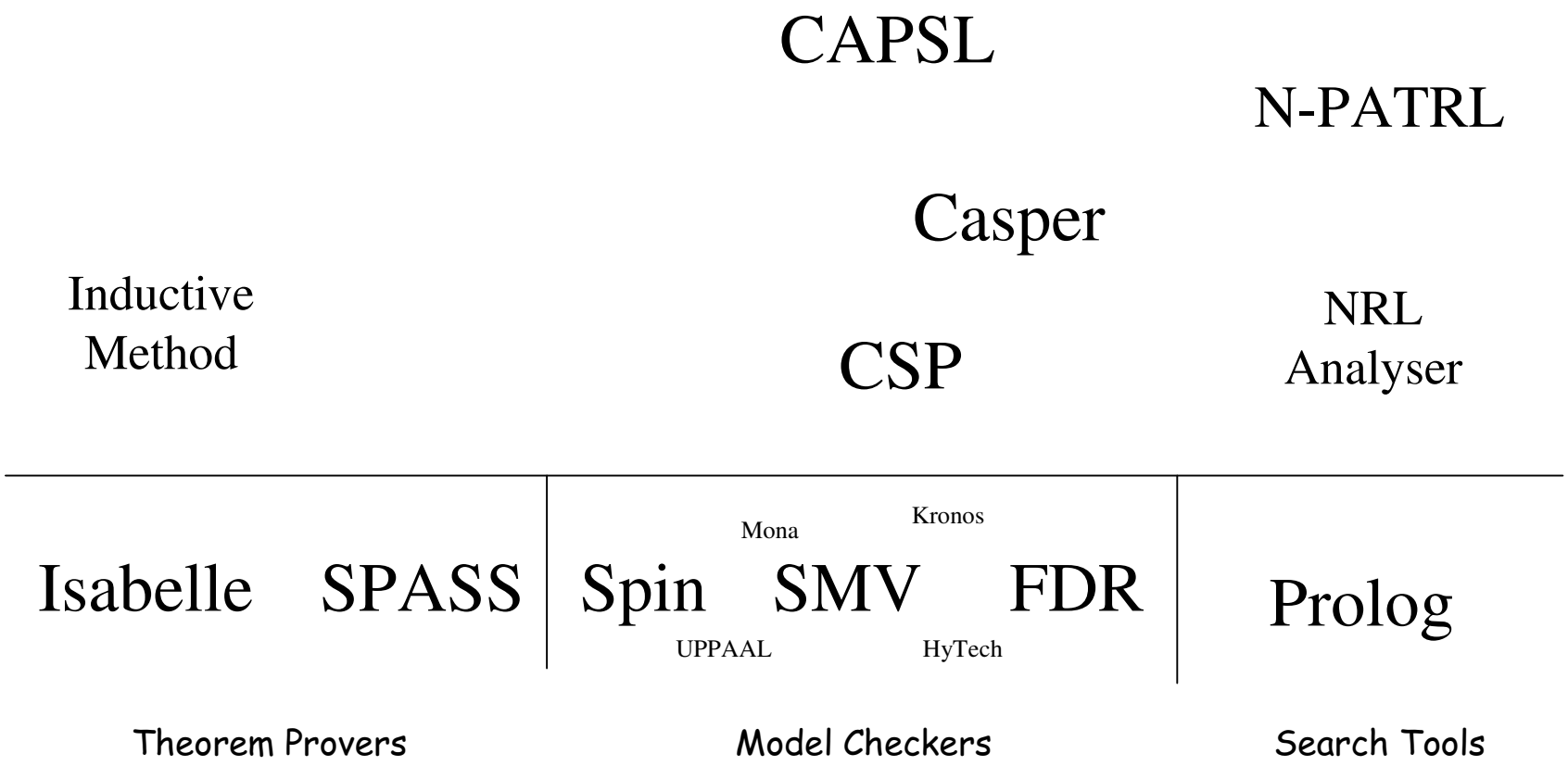
- Found at trust boundary of tamper-resistant processors which use cryptography to control processing of and access to sensitive data



Why Automate API Analysis?

- APIs are getting more complex – more human effort required, and few skilled people
  - VSM Banking API ’89 – 80 pages
  - CCA Banking API ’02 – 458 pages
- Can make finding attacks quicker
- Can spot stupid mistakes at once
- Might one day find an attack of its own accord?
- Can search for all instances of a known attack
- Operating tool can help build intuitive knowledge

Protocol Analysis Tools



Formalising APIs

1. Read specification (or instruction manual)
2. Decide on primitives required
3. Choose analysis tool supporting primitives
4. Formalise each command
5. Test against known attacks
6. Patch to prevent known attacks
7. Search for unknown attacks

Example Pages from IBM Manual

Data_Key_Import (CSNBDKM)

Platform/ Product	OS/2	AIX	NT	OS/400
IBM 4758-1	X	X	X	X

The Data_Key_Import verb imports an encrypted, source DES DATA key and creates or updates a target internal key token with the master-key enciphered source key. The verb can import the key into an internal key token in application storage or in key storage. This verb, which is authorized with a different control point than used with the Key_Export verb, allows you to limit the export operations to DATA keys as compared to the capabilities of the more general verb.

Specify the following:

- An external key token containing the source key to be imported. The external key token must indicate that a control vector is present; however, the control vector is usually valued at zero.

  Alternatively, you can provide the encrypted data key at offset 16 in an otherwise all X'00' key token. The verb will process this token format as a DATA key encrypted by the importer key and a null (all zero) control vector.
- An IMPORTER key-encrypting key under which the source key is deciphered.
- An internal or null key token. The internal key token can be located in application data storage or in key storage.

The verb builds the internal key token by the following:

- Creates a default control vector for a DATA key type in the internal key token, if the control vector in the external key token is zero. If the control vector is not zero, the verb copies the control vector into the internal key token from the external key token.
- Multiply-deciphers the key under the keys formed by the exclusive-OR of the key-encrypting key (identified in the *importer_key_identifier*) and the control vector in the external key token, then multiply-enciphers the key under keys formed by the exclusive-OR of the master key and the control vector in the internal key token. The verb places the key in the internal key token.
- Calculates a token-validation value and stores it in the internal key token.

This verb does not adjust the key parity of the source key.

Restrictions

None

Format

CSNBDKM			
return_code	Output	Integer	
reason_code	Output	Integer	
exit_data_length	In/Output	Integer	
exit_data	In/Output	String	*exit_data_length* bytes
source_key_token	Input	String	64 bytes
importer_key_identifier	Input	String	64 bytes
target_key_identifier	In/Output	String	64 bytes

Parameters

For the definitions of the *return_code*, *reason_code*, *exit_data_length*, and *exit_data* parameters, see "Parameters Common to All Verbs" on page 1-10.

source_key_token
The *source_key_token* parameter is a pointer to a 64-byte string variable containing the source key to be imported. The source key must be an external key.

importer_key_identifier
The *importer_key_identifier* parameter is a pointer to a 64-byte string variable containing the (IMPORTER) transport key used to decipher the source key.

target_key_identifier
The *target_key_identifier* parameter is a pointer to a 64-byte string variable containing a null key token, an internal key token, or the key label of an internal key token or null key token record in key storage. The key token receives the imported key.

Required Commands

The Data_Key_Import verb requires the Data Key Import command (offset X'0109') to be enabled in the hardware.

Command Formalisation

The following transactions are used to translate PINs, that is, to decrypt an encrypted PIN block and re-encrypt it under another key. During the process, the PIN block format itself may be changed if desired.

These transactions are used on interchange networks. For example, if a foreign cardholder uses your ATM, the ATM typically makes his PIN up into a PIN block, encrypts it under a local key (a terminal PIN key) and sends it to you. You then use 'CA' to translate this PIN block from the local key to the acquirer working key you currently use with the switch in question.

Note that you don't use a communication key to encrypt PINs on the ATM link, since then one of your application programmers could write code to determine the PINs of other institutions' cardholders - precisely the type of attack the is designed to thwart.

TRANSACTIONS CA/CC - TRANSLATE A PIN

Host Message:

Field	Type	Description
Header	4 Alpha	Returned unchanged
Trancode	2 Alpha	'CA' - translate from a local key to an interchange key 'CC' - translate from one interchange key to another
Source key	16 Hex	CA: the local key encrypted under keys 14 & 15 CC: any interchange key encrypted under keys 6 & 7
Destination key	16 Hex	The interchange key (eg AWK) encrypted under keys 6 & 7
Filler	2 Decimal	'12'
Source PIN block	16 Hex	The PIN block encrypted under the source key
Source PIN format	2 Decimal	The format of the source PIN block - these are detailed in the appendix
Destination PIN format	2 Decimal	The format to which you want the PIN block to be converted
Account no.	12 Decimal	The 12 rightmost digits of the account number, excluding the check digit

Response Message:

Field	Type	Description
Header	4 Alpha	Returned unchanged
Trancode	2 Alpha	'CB' in response to CA 'CD' in response to CC
Return code	2 Decimal	One of the N3000SM return codes
PIN length	2 Decimal	Length of the returned PIN
PIN block	16 Hex	Encrypted under the destination key
PIN format	2 decimal	'Destination PIN format' above

Note: the PIN formats in brief are 01: ANSI; 02: Docutel I; 03: IBM/ Docutel II. FNB, Saswitch and VISA currently use format 03.

The rest of the transactions in this chapter are for translating various keys.

TRANSACTION FA - RECEIVE A WORKING KEY FROM A SWITCH

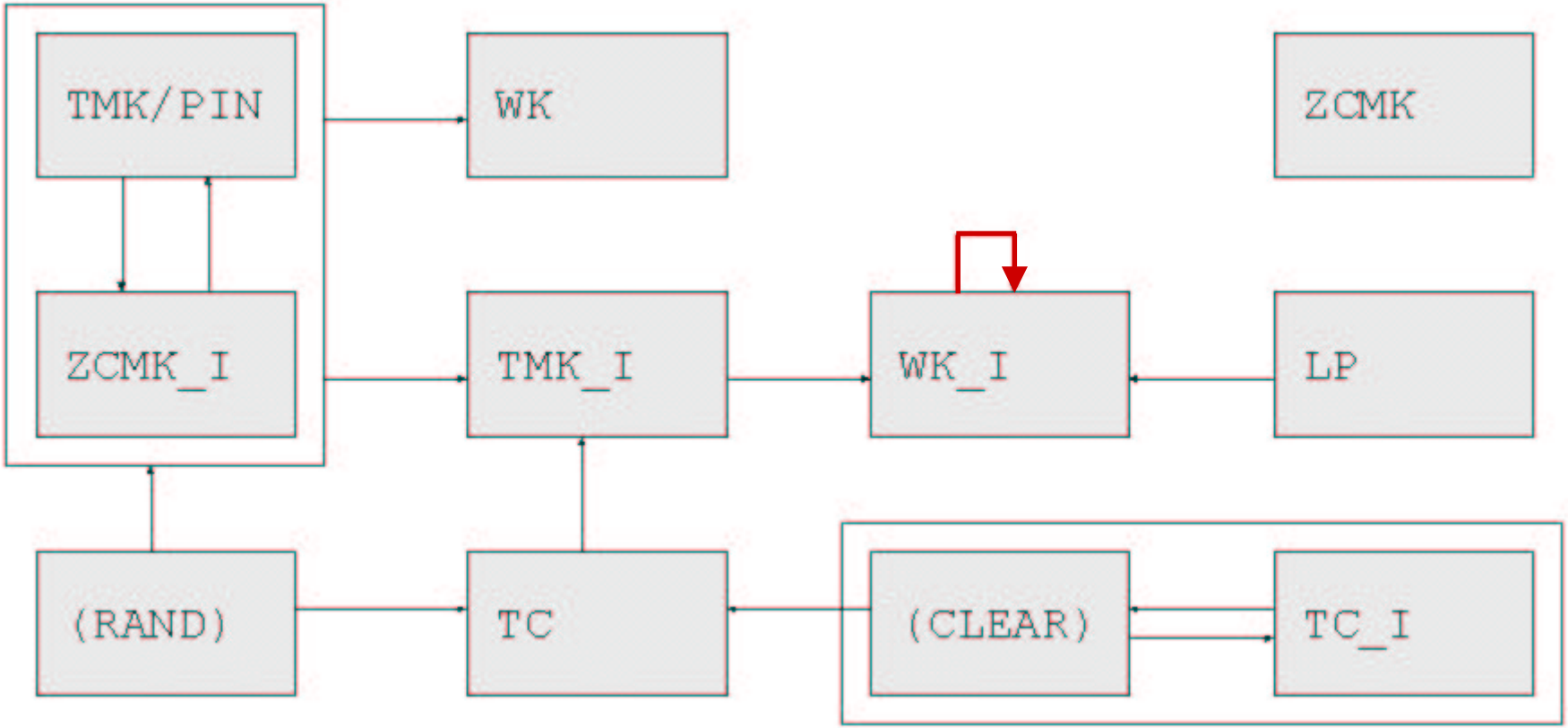
Host Message:

Field	Type	Description
Header	4 Alpha	Returned unchanged
Trancode	2 Alpha	'FA'
ZCMK	16 Hex	Encrypted under master keys 4 & 5
Key(ZCMK)	16 Hex	The working key from the switch, encrypted under the ZCMK

Response Message:

Field	Type	Description
Header	4 Alpha	Returned unchanged
Trancode	2 Alpha	'FB'
Return code	2 Decimal	One of the N3000SM return codes
Key(KM)	16 Hex	The working key, encrypted under 6 & 7

Command ‘CC’ Formalised



Command ‘CC’ Formalised

$$U \rightarrow C : \{ D \}_{WK1} , \{ WK1 \}_{WK} , \{ WK2 \}_{WK}$$

$$C \rightarrow U : \{ D \}_{WK2}$$

```
formula( forall([X,Y,Z], implies(
   and(public(X),and(public(Y),public(Z))) , public(
   enc(enc(i(wk),Z),enc(i(enc(i(wk),Y)),X))) )
```

```
A = !< ( { X }Y , { Y }WK , { Z }WK ) > . ?(x).[ x = { X }Y ]
B = ?(x) . case x of ( { w }y , { y }WK , { z }WK ) in !< { w }z > . 0
```

Command ‘CC’ Formalised

```
Cmd "CC_Data_Translate_Between_Interchange_Keys"
        Input ENC(ANY,ANY)
        Input ENC(WK,ANY)
        Input ENC(WK,ANY)
        Output ENC( DEC(WK,TWO) , DEC( DEC(WK,ONE) , ZERO ) )
End_Cmd
```

What else needs Formalising?

Protocol-Speak	**API-Speak**
already…	
Protocol Messages	Command Definitions
also…	
Environment	Initial Knowledge
Attacker's Abilities	N/A
Security Requirements	Initial Goals
# of Runs of Protocol	Search Depth
# of Concurrent Runs	N/A

Experiments with SPASS

- SPASS used in its capacity as a first order logic (FOL) theorem prover
- Predicate ‘public’ used to define commands and knowledge e.g.

```
public(input) => public(f(input))
```

- Try to prove assertion `public(a_secret)`
- Sit back and wait…

SPASS Output...

```
------------------------- SPASS START -----------------------
PING PING PING PING PING PING PING PING
PING PING PING PING PING PING PING PING
PING PING PING PING PING PING PING PING
PING PING PING PING PING PING PING PING
PING PING PING PING PING PING PING PING
PING PING PING PING PING PING PING PING
PING PING PING PING PING PING PING PING

(and so on...)
```

Why SPASS is Unsuitable

- Insufficient runtime feedback
- Insufficient documentation
- Too many (unexplained) parameters to tweak – over 90 command line options
- SPASS correctly rediscovered every step and pair of steps of an attack, but could not discover the attack all in one go
- Unclear how to best re-express the problem

Other Tools?

- Wide choice (15-20 tools)
- Quality of documentation variable; many concentrate upon the tool's application to a particular specialised problem
- Decided to learn from building my own tool …

"the only way to understand the wheel is to reinvent it"

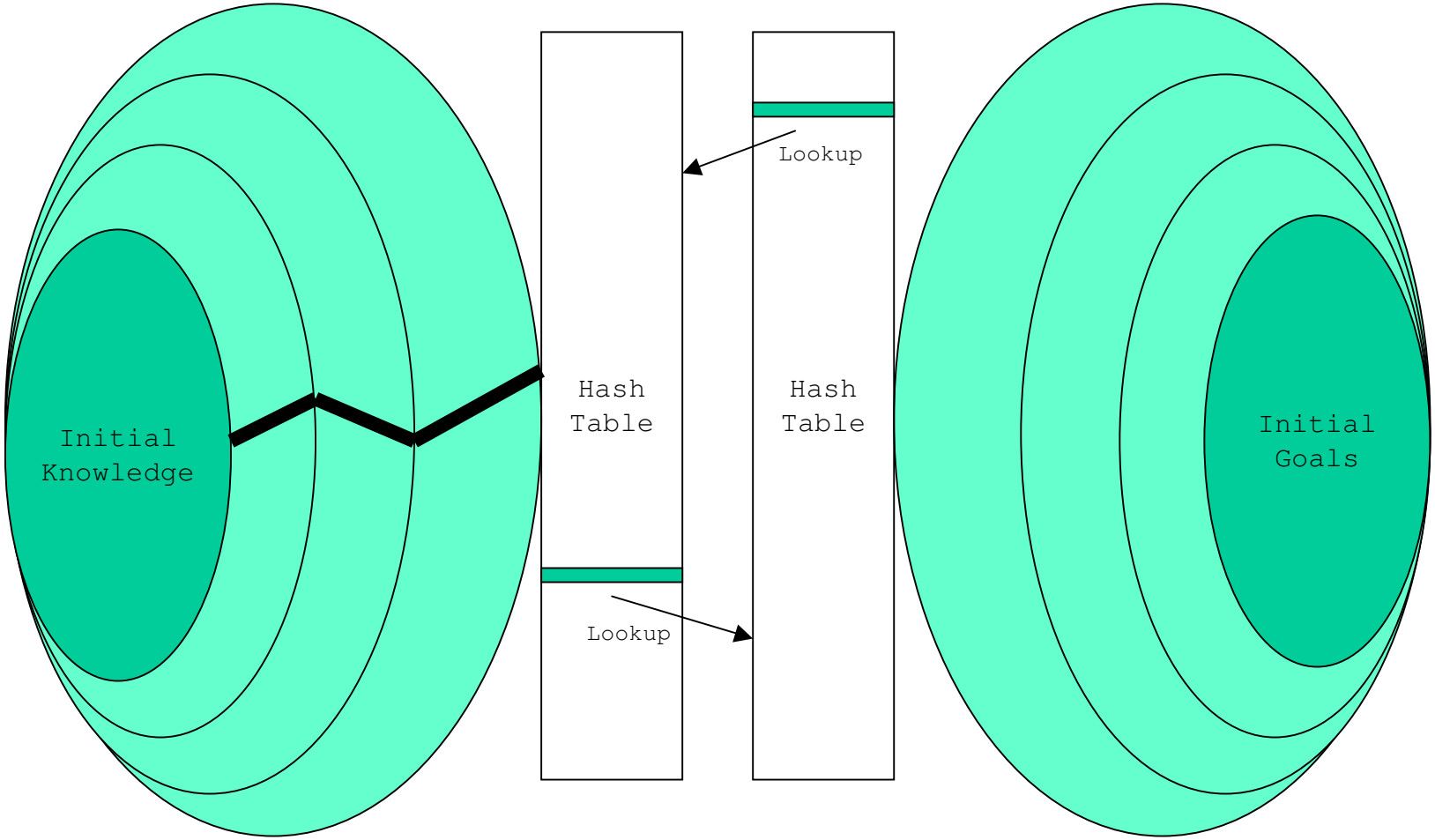
Mimsearch Tool : Goals

- Learn about strengths and weaknesses of model checkers and theorem provers through comparison with a well understood example
- Improve ability to effectively use existing tools through better understanding of their internal working
- Determine the minimum complexity of models that can capture all known API attacks
- Create a tool powerful enough to reason about financial APIs, especially those using control vectors (ie. XOR)

Mimsearch Tool : Non-Goals

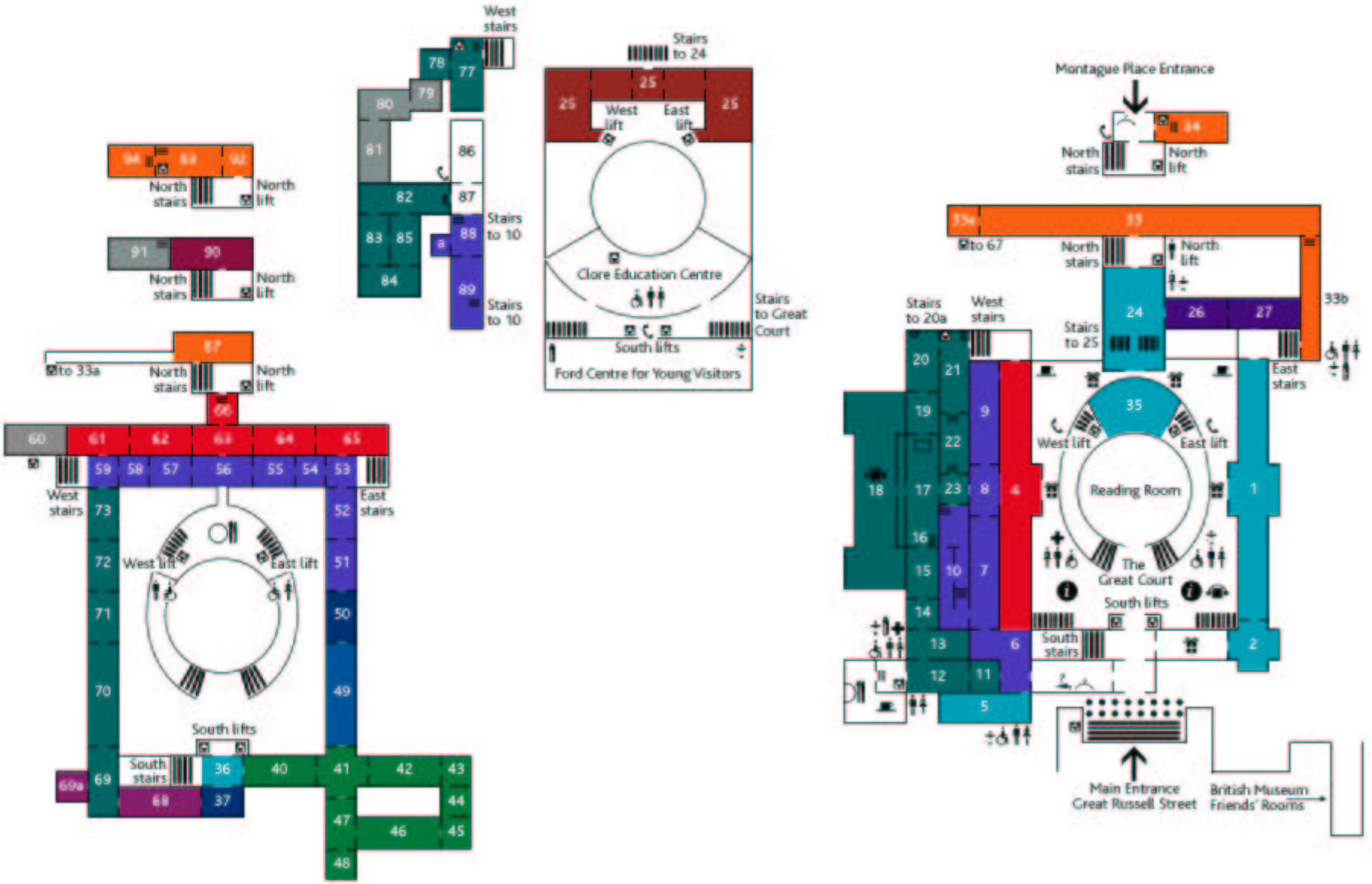
- Produce a tool more powerful than tool X
- Produce a better documented tool than tool X
- Produce an implementation for public release

Core Idea : Meet-in-the-Middle



“The British Museum”

“The British Museum”



Core Idea : Exploring the Museum

Core Ideas : Summary

- Attack the state space from both directions
- Minimise the number of heuristics: “Intelligent” search damages state space, and reduces chance of finding new attacks
- Accurately measure the state space: more accurate bounds mean more accurate assessment of security
- Native support for XOR and cryptographic primitives
- Understand the search : proper diagnostics should be available to all users

Implementation Tour

- Problem Specification
- Symbolic Term Manipulation Engine
- Search Threads
- Reverse Execution
- Hash Tables
- Distributed Computing Support
- Diagnostics

Problem Specification

```
Begin_Transaction_Set("4758-testset")

          Begin_Cmd_List
          End_Cmd_List

          Begin_Reverse_Cmd_List
          End_Reverse_Cmd_List

          Begin_Atom_List
          End_Atom_List

          Begin_Attack

                    Begin_Initial_Knowledge_List
                    End_Initial_Knowledge_List

                    Begin_Initial_Goal_List
                    End_Initial_Goal_List

                    Search_Depth 3

          End_Attack

          Begin_Wat_List
          End_Wat_List

End_Transaction_Set
```

Definitions of Commands

Definitions of Command Inverses

List of Atoms

Starting Point

Goal

Diagnostics List

Problem Spec Parser

- Transaction set language parsed at compile time using ugly mess of C preprocessor and compiler.
- Minimal effort put in because there are few transaction sets, they change rarely, and parsers are difficult.

Command Representation

$$U \rightarrow C : \{ D \}_{WK1} , \{ WK1 \}_{WK} , \{ WK2 \}_{WK}$$

$$C \rightarrow U : \{ D \}_{WK2}$$

```
Cmd "CC_Data_Translate_Between_Interchange_Keys"
        Input ENC(ANY,ANY)
        Input ENC(WK,ANY)
        Input ENC(WK,ANY)
        Output ENC( DEC(WK,TWO) , DEC( DEC(WK,ONE) , ZERO ) )
End_Cmd
```

More Example Commands

```
Begin_Cmd_List

// Ability_XOR
   Cmd "Ability XOR"
        Input ANY
        Input ANY
        Output XOR(ZERO,ONE)
   End_Cmd

// Key_Part_Import
Cmd "Key_Part_Import"
      Input ENC(XOR(KM,CV_IMP_PART),ANY)        // X, kek_part_token
     Input ANY                                  // Y, new XOR value
     Output ENC(XOR(KM,CV_IMP),XOR(DEC(XOR(KM,CV_IMP_PART),ZERO),ONE))
End_Cmd

// Key_Import
Cmd "Key_Import"
     Input ENC(XOR(ANY,ANY),ANY)     // W, ext_token
     Input ENC(XOR(KM,CV_IMP),ANY)               // X, kek_token
     Input ANY                       // Y, claimed_type
     Output ENC(XOR(KM,TWO),DEC(XOR(DEC(XOR(KM,CV_IMP),ONE),TWO),ZERO))
End_Cmd

// Encrypt  (NOT Ability_Encrypt)
Cmd "Encrypt"
     Input ENC(XOR(KM,CV_DATA),ANY)
     Input ANY
     Output ENC(DEC(XOR(KM,CV_DATA),ZERO),ONE)
End_Cmd

End_Cmd_List
```

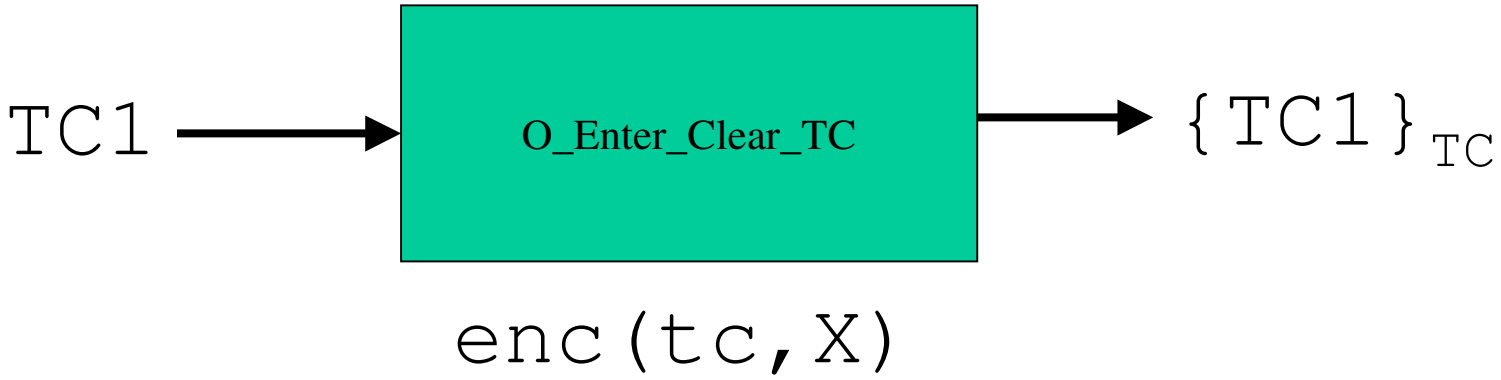
Symbolic Term Manipulation Engine

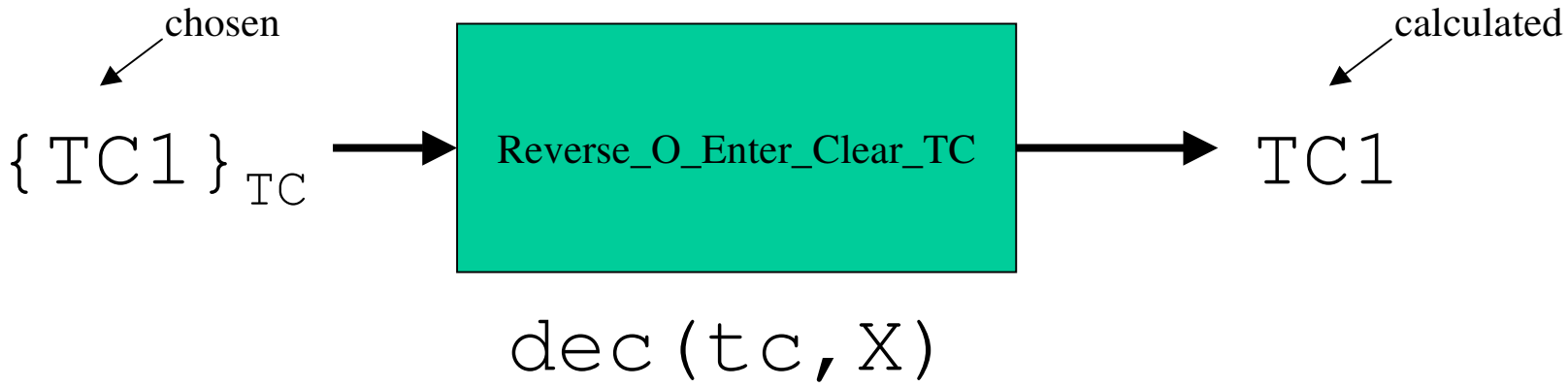
- Terms represented as trees of objects
- reduce, rehash, substitute and pattern match methods
- subtree hashes stored to speed up pattern matching
- This part is most sensitive to bugs – wrong manipulations will invalidate analyses
- Worked hard to remove bugs, but conservative implementation is not optimised for speed

Search Threads

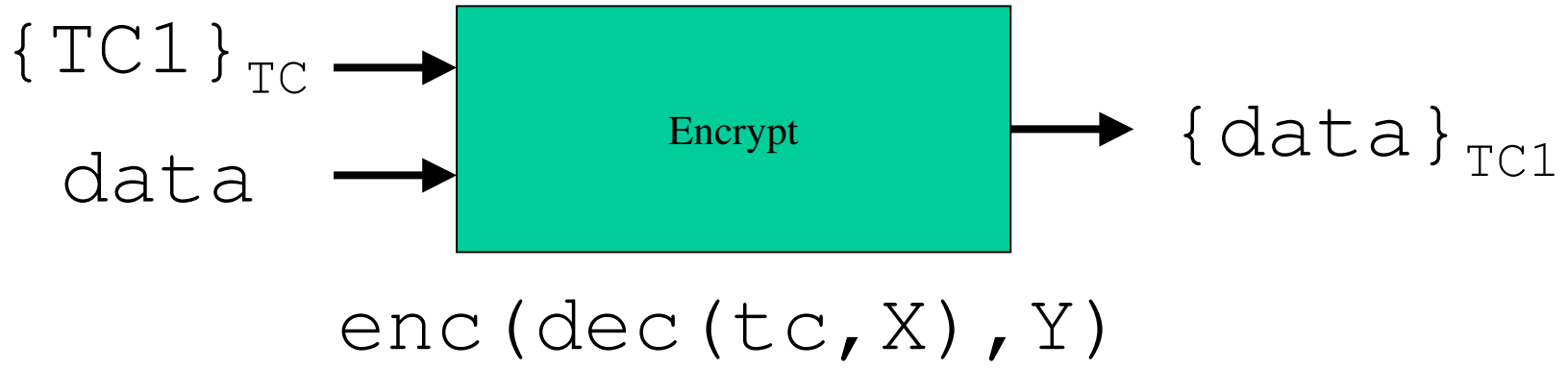
- Search threads for both forward and backward search
- Pseudo-Random Number Generator seeded with strong(ish) random number representing each path, then called by all random decision making code owned by that thread
- Plausible command and argument selected (optionally according to likely reduction filters)
- Command executed as substitutions followed by a reduction to normal form
- Resulting term checked for match against hash table from search in the other direction
- Resulting term added (temporarily) to initial knowledge, and registered with hash tables

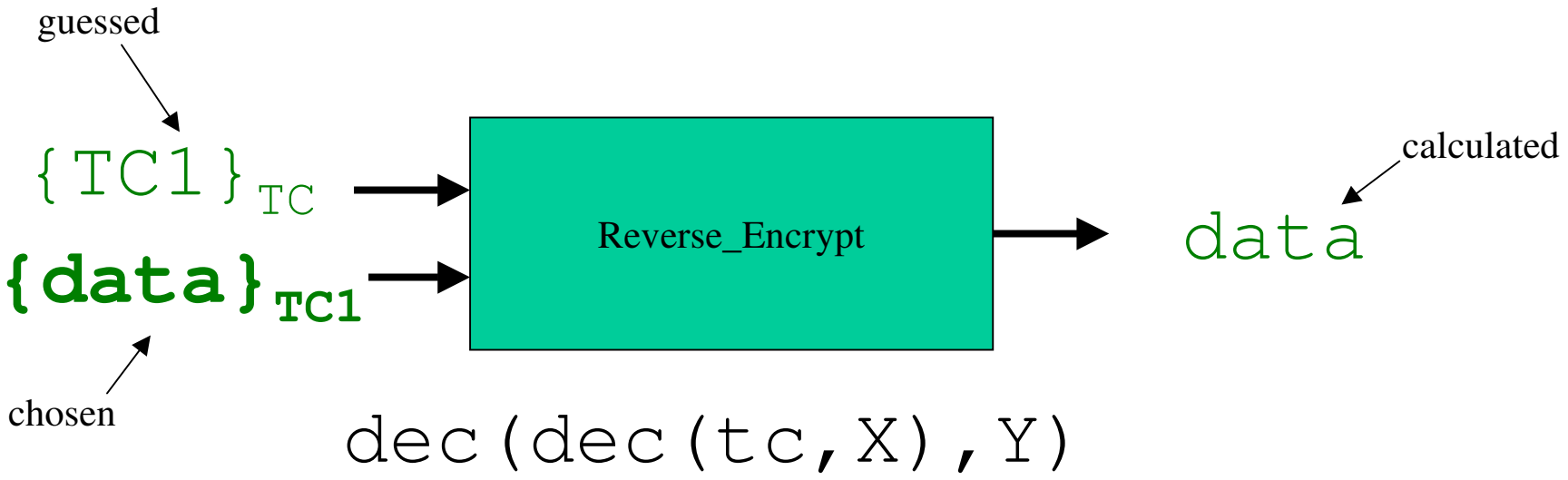
Reverse Execution Logic



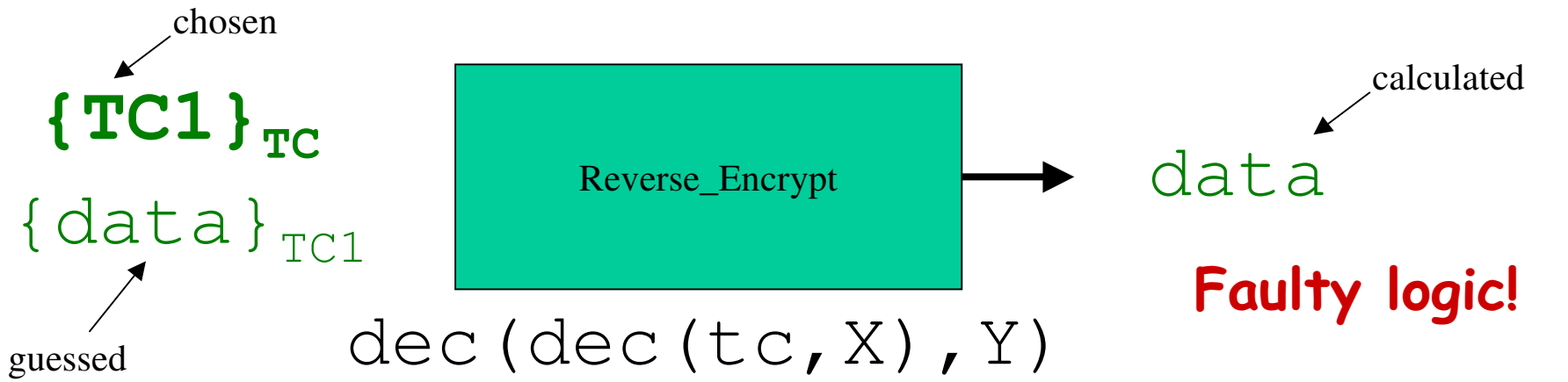


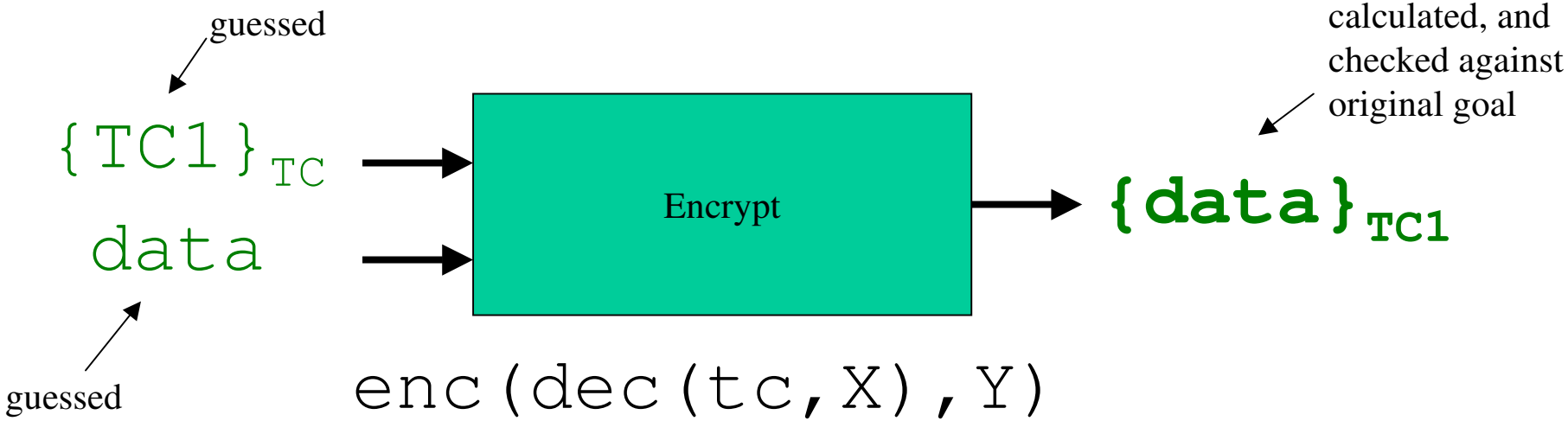
Reverse Execution : Dual Inputs





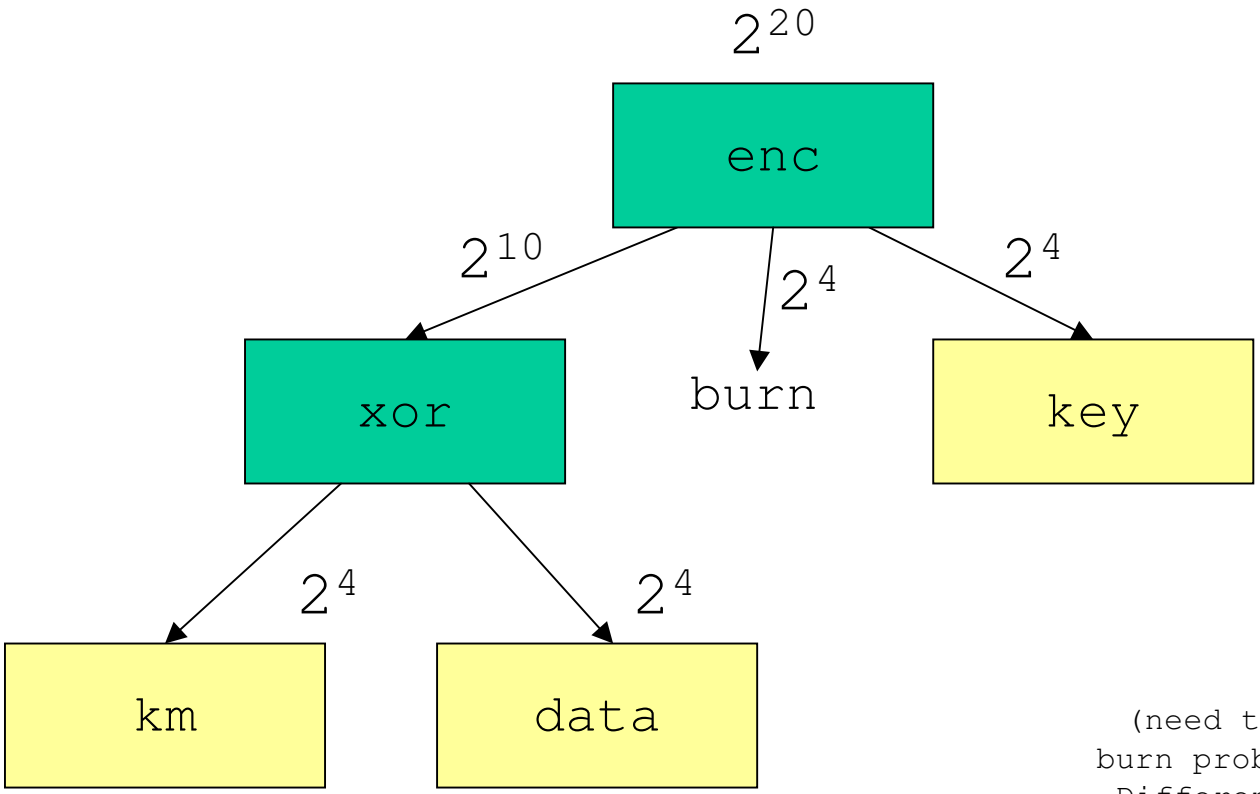
Problems with Reverse Execution





Entropy Limited Term Invention

enc(xor(km,data),key)



(need to specify burn probability at Different depths)

Hash Tables

- First implementations small sized (20MB), but current implementation uses 400MB per machine
- Windows 2000 behaves unpredictably when high demands are made on memory – caused lots of difficulty.
- What should the hash table store?
  - single bit markers (chosen)
  - partial storage of seed
  - storage of whole hash
- Birthday paradox makes false collisions (i.e. different terms with the same hash) very likely. Collisions require human intervention, so hash table must be as big as possible if system is to stay up unattended for more than a few minutes

Distributed Computing Support

- Manual logon of 50 machines takes about 15 mins
- Client/Server architecture between control machine and search machines using persistent TCP/IP connections
- Control machine connects to searchers, and collates diagnostic and result information (main communications workload), and routes it on to the graphical user interface.
- Control machine will later take responsibility for routing information for distributed hash tables. Searchers will probably form fully connected mesh

Diagnostics

- Watch display for progress towards known attack (total hits & hit rate)
- Hash table growth statistics
- Statistics combined across machines
- Complexity & search rate reports
- Runtime command line interface

  (esp. for debug)

Watch Display

Statistics


MDM Model Checker
Statistics
Control
Debug
Watch
Output
READY
Results Connection OK
Debug Messages
26/06/02 V1.8.R2.3 READY
Debug Connection OK
vsse ad. Ready

Control & Configuration

Results

Attack	Complexity	# Commands	Time Taken
VSM XOR to null key	$2^{66.1}$	5	5 mins
VSM type-cast	2^{38}	3	<1 sec
4758 CCA type-cast	2^{57}	5	30 secs

Scalability and Future Limits

- Should be scalable up to about 2^{80} search path space
  - requires several terabytes for hash table
  - equivalent to two 2^{40} searches in each direction
  - relies upon continued success with reverse command execution
- Larger computer cluster could be used – over 1,000 machines in entire PWF, only 50 in practical laboratory
- FPGA hardware technology? Compile transaction set into hardware search machine?

Conclusions

- Security APIs are amenable to analysis for several sorts of attack
- The British Museum algorithm is alive and well
- Birthday attacks are an extremely useful tool
- Many more interesting problems can be brought within range of current formal analysis techniques by applying engineering know-how
- We need to expend more effort measuring the difficulty of problems
  - Question: Can the complexity bounds of a random search through an API be narrowed in polynomial time?"
- We need to develop instinctive understanding of complexity consequences as new transaction sets are written, or existing ones are formalised (complexity theoretic editor?)

More Information

http://www.cl.cam.ac.uk/~mkb23/research.html

Academic paper by Feb 2003?