Three decades of success stories in formal methods

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Context of this work

- A study on formal methods launched in 2011 by the German BSI (federal office on security in information technology)

- Currently, formal methods are not so widely used – mostly in niche applications

- Can we prove to (industrial or governmental) managers that formal methods are useful?

A frequent answer: failure stories

- List of well-known software failures:
  - Therac 25 radiation therapy engine
  - Denver airport
  - Patriot missile interceptor
  - Pentium 5 division algorithm
  - Ariane 5.01 maiden flight
  - Mars orbiter
  - etc.
- But:
  - these are disaster stories
  - they threaten the audience, but do not prove that formal methods would have enabled to avoid such failures

Be positive!

- Try to convince rather than threaten
- Find success stories, not disaster stories

Related studies (1)

There already exist formal methods surveys:

- Craigen, Gerhart & Ralston 1993, 1994, 1995
  - 12 case studies
  - old and unbalanced: SCR (formulas and tables), B, CAS logic, Gypsy (1st order predicate calculus), Z, Z, Cleanroom, Z, RAISE, Z+Occam, RAISE, VDM
  - nothing about protocol or hardware verification
- Clarke & Wing 1996
  - 22 pages
  - rich and dense
  - quite exhaustive and fair, but 16 years-old now

Related studies (2)

- Woodcock, Larsen, Bicarregui & Fitzgerald 2009
  - 40 pages
  - rich and deep
  - but a bit biased:
    - towards "US+UK" and "paper and pencil" methods
    - against model checking (admitted)
    - (not a word about the PRISM model checker!)
  - 8 featured projects (Section 4): Z+CSP, B, Z, RAISE+PVS+ACL2, SCADE, Z+SPIN, SPARK, VDM++
- Haxthausen 2010
  - 32 pages, a bit superficial, not balanced
  - 6 case studies: B, B, B, RAISE, SPIN, Z

Related studies (3)

- Dagstuhl 2010 Manifesto
  - comprehensive panorama
  - no case studies
- www.fm4industry.org
  - famous formal methods success stories
  - 8 case studies listed (1980-2009)
- www.fmsurvey.org
  - survey on industrial use of formal methods (2011)
  - 62 projects considered
  - 34% agree and 61% strongly agree that using formal methods was successful

A different methodology

- How to ensure:
  - a larger coverage over years?
  - a greater diversity of approaches and methods?
  - a better balance between countries?

- Idea:
  - Review 3 decades (from 1982 to 2011 included)
  - Select one "success story" each year

  => 30 featured case studies

Selection criteria

- Focus on concrete **applications** of formal methods, rather than theoretical discoveries or software tool releases
- Many applications took several years: the year of first publication is chosen, rather the dates of start or end of the project (often unknown or unclear)
- Avoid selecting the same approach twice

Difficulties (1)

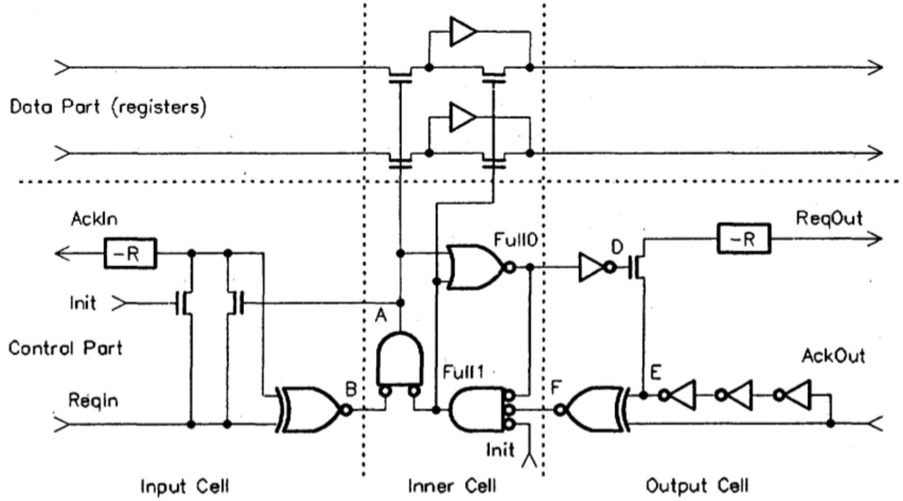
- Exhaustivity is impossible:
  - Only 30 slots for a large formal methods community
  - Google Scholar: 220,000 answers for "formal methods"
  - Nearly 4000 scientists in verification [Woodcock et al]
    - USA : 1000 scientists in verification [Shankar 2009]
    - Europe : 1000
    - Nordic countries : 500
    - China : 250
    - Japan : 250
    - Australia / New Zealand / Brazil / Canada / Singapore / South Africa : 1000

Difficulties (2)

- The problem (finding one single "success story" per year) is perhaps over-constrained
- In recent years, there are several convincing applications of formal methods. No one is really the "best"
- Priority to case studies that were influential and/or reproduced later independently
- Some "tweaking" needed on publication dates (conference vs journal, etc.)

1982

[Bochmann]
[Fujita-Tanaka-Moto Oka]
[Clarke-Mishra-Browne-Dill]

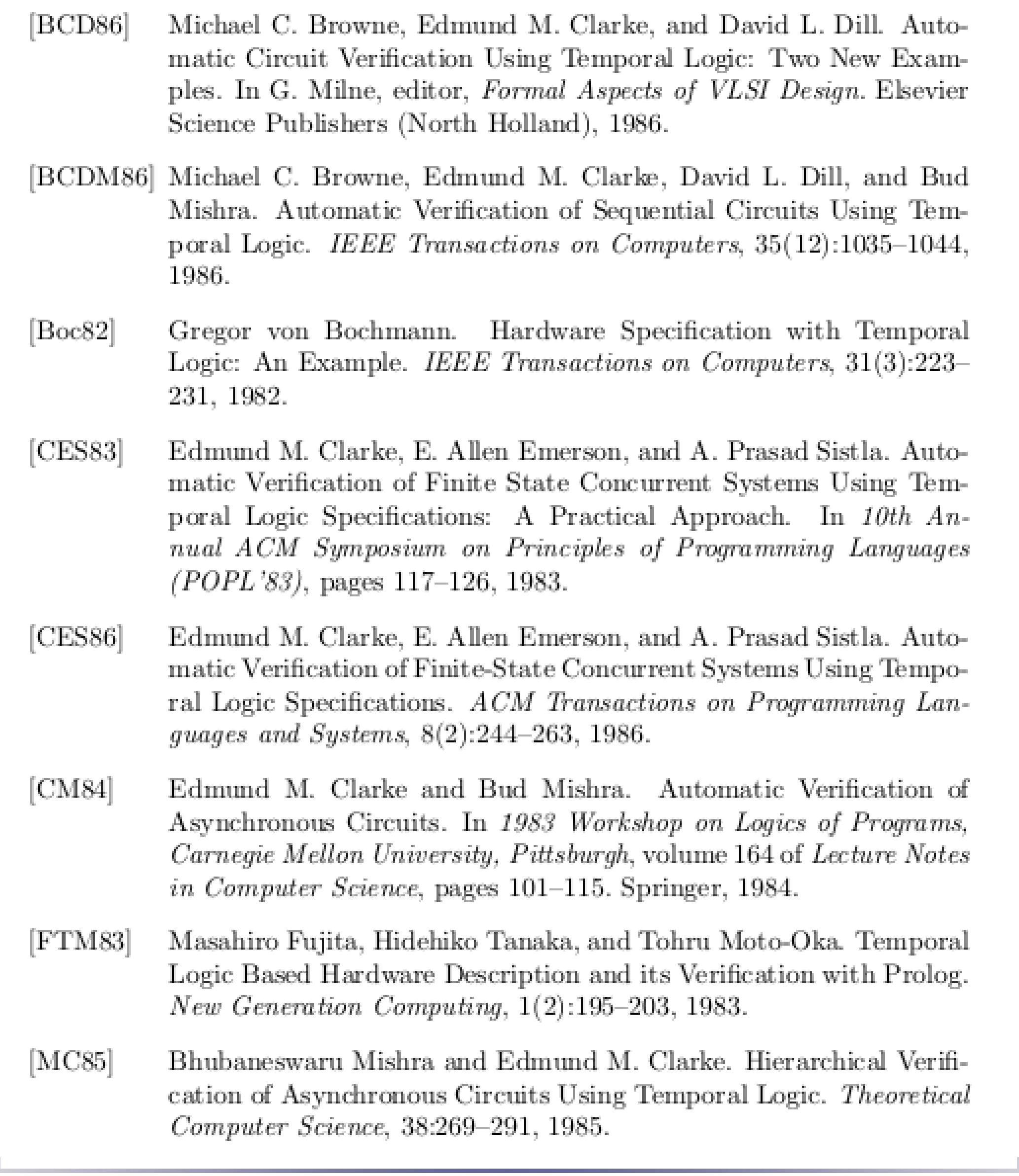


Formal specification, using temporal logic, of asynchronous circuits and sequential circuits

Verification of these circuits using state-space exploration and/or model checking

The EMC model checker revealed an error in a FIFO queue circuit element published in a popular textbook on VLSI design

[1982]



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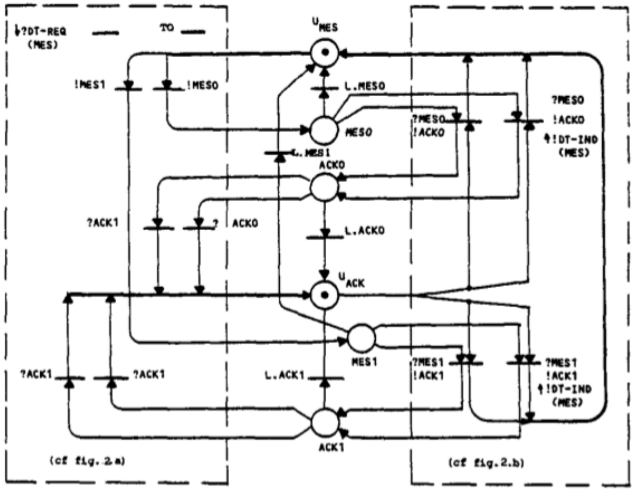
1983

[Billington-Bearman-Wilbur Ham]
[Courtiat-Ayache-Algayres]
[Jürgensen-Vuong]



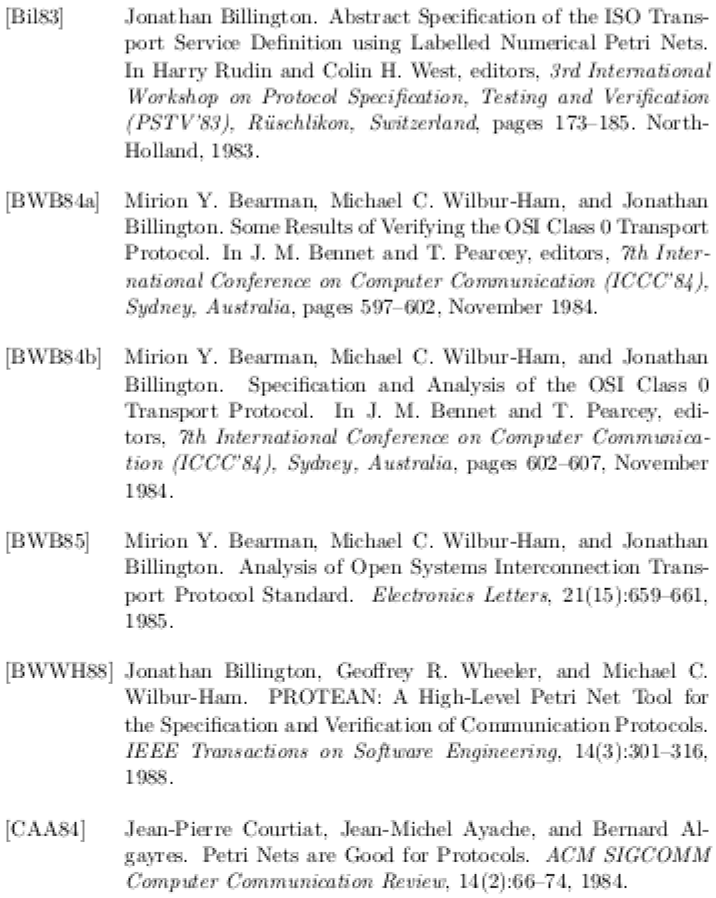
a) Global model interconnection
FIGURE 4. Alternating bit protocol and service

Formal specifications with (extended Petri nets) of the OSI transport layer protocol

Three independent teams, one using the PROTEAN tool (Austria) and two using the OGIVE/OVIDE tool (France)

Various properties checked (general, specific, structural). No harmful error found

[1983]



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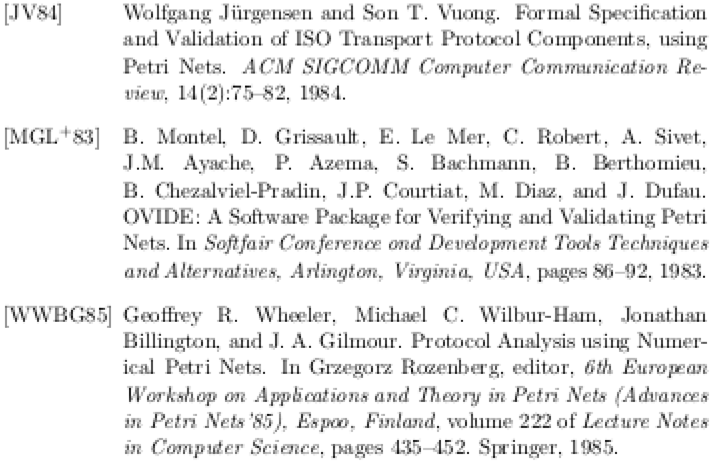
[1983]



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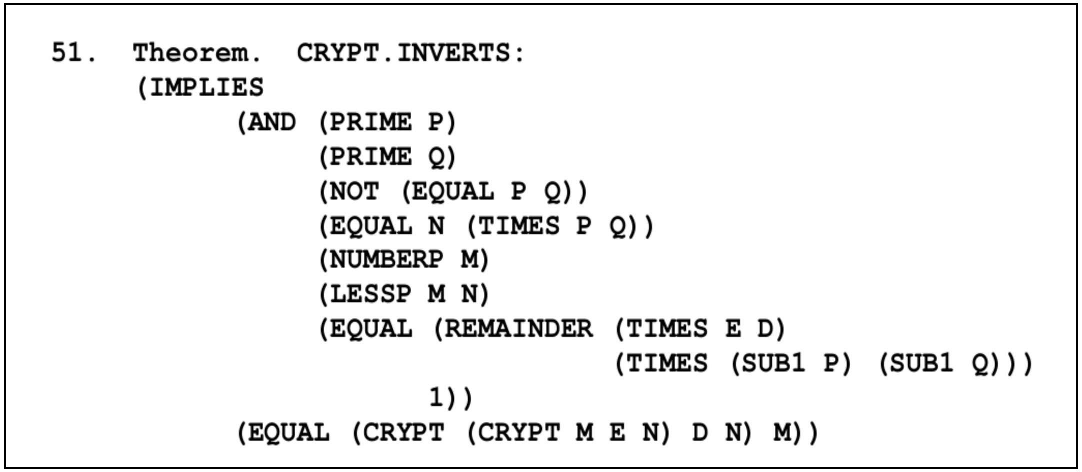
1984

[Boyer-Moore-Shankar]



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51.  Theorem.  CRYPT.INVERTS:
     (IMPLIES
           (AND (PRIME P)
                (PRIME Q)
                (NOT (EQUAL P Q))
                (EQUAL N (TIMES P Q))
                (NUMBERP M)
                (LESSP M N)
                (EQUAL (REMAINDER (TIMES E D)
                                  (TIMES (SUB1 P) (SUB1 Q)))
                       1))
           (EQUAL (CRYPT (CRYPT M E N) D N) M))
```

Automated proof checking using the NQTHM (Boyer-Moore) theorem prover of fundamental theorems of computer science:

– unsolvability of the halting problem,

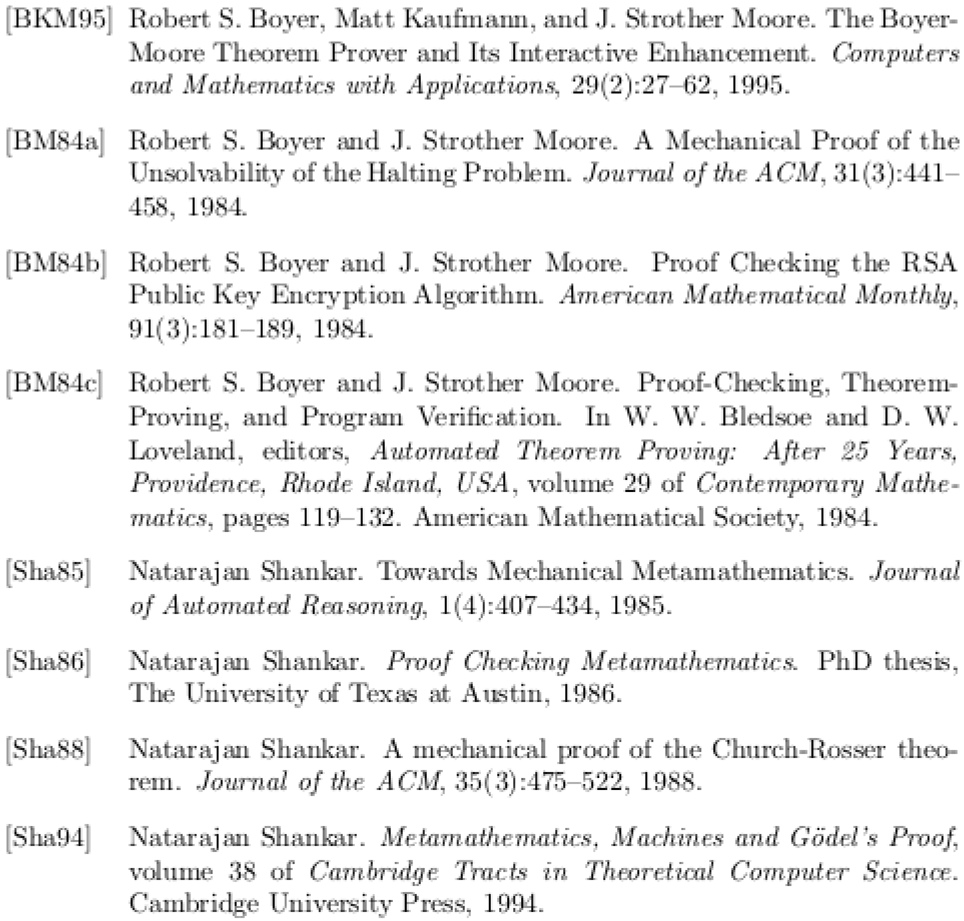
– Gödel's first incompleteness theorem

– Church-Rosser theorem of λ-calculus

and other theorems of practical value:

– invertibility of the RSA encryption algorithm

[1984]



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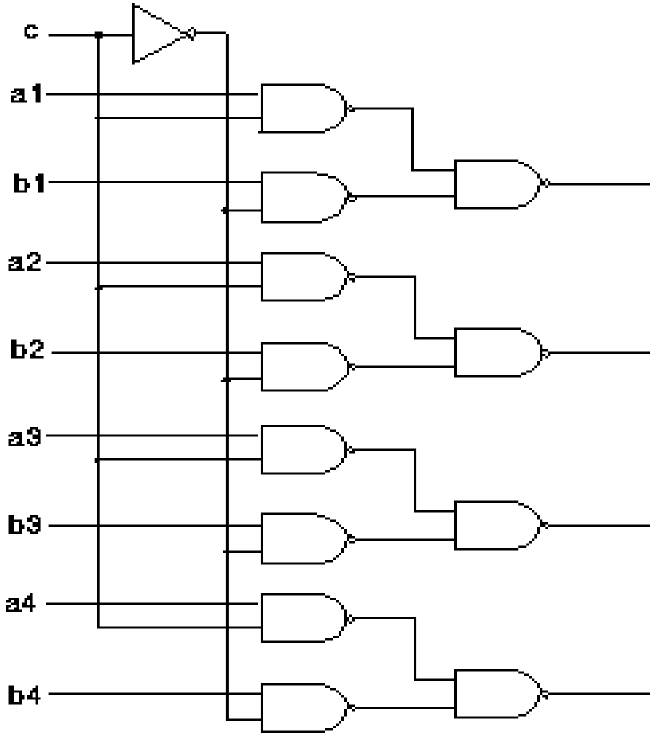
1985

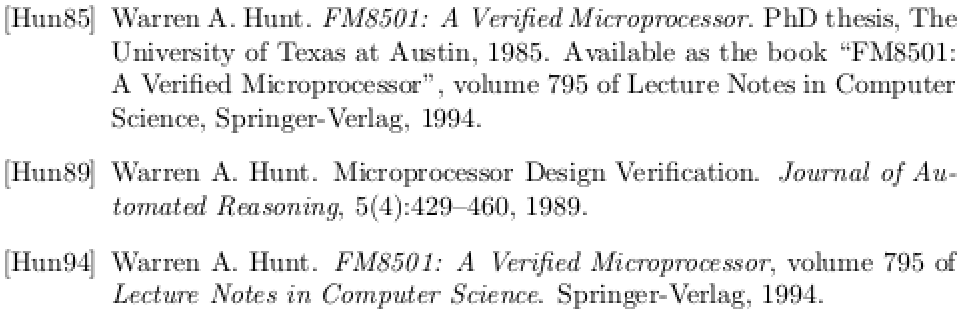


[Hunt]

Formal verification of the 16-bit FM8501 microprocessor using the NQTHM theorem prover

This was the first verified microprocessor, followed by many others

[1985]



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1986

[West] + [Rudin, Zafiropulo]

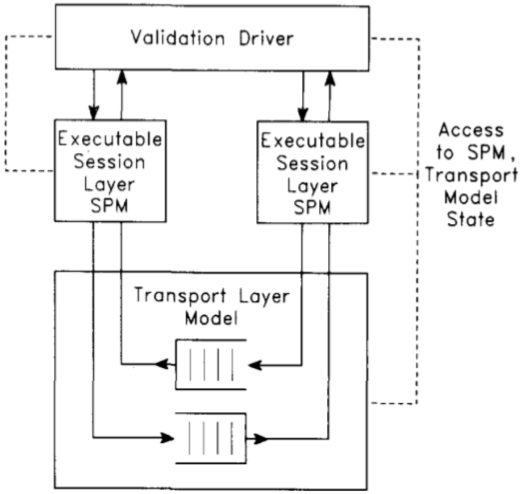

Validation Driver
Executable Session Layer SPM
Executable Session Layer SPM
Access to SPM, Transport Model State
Transport Layer Model

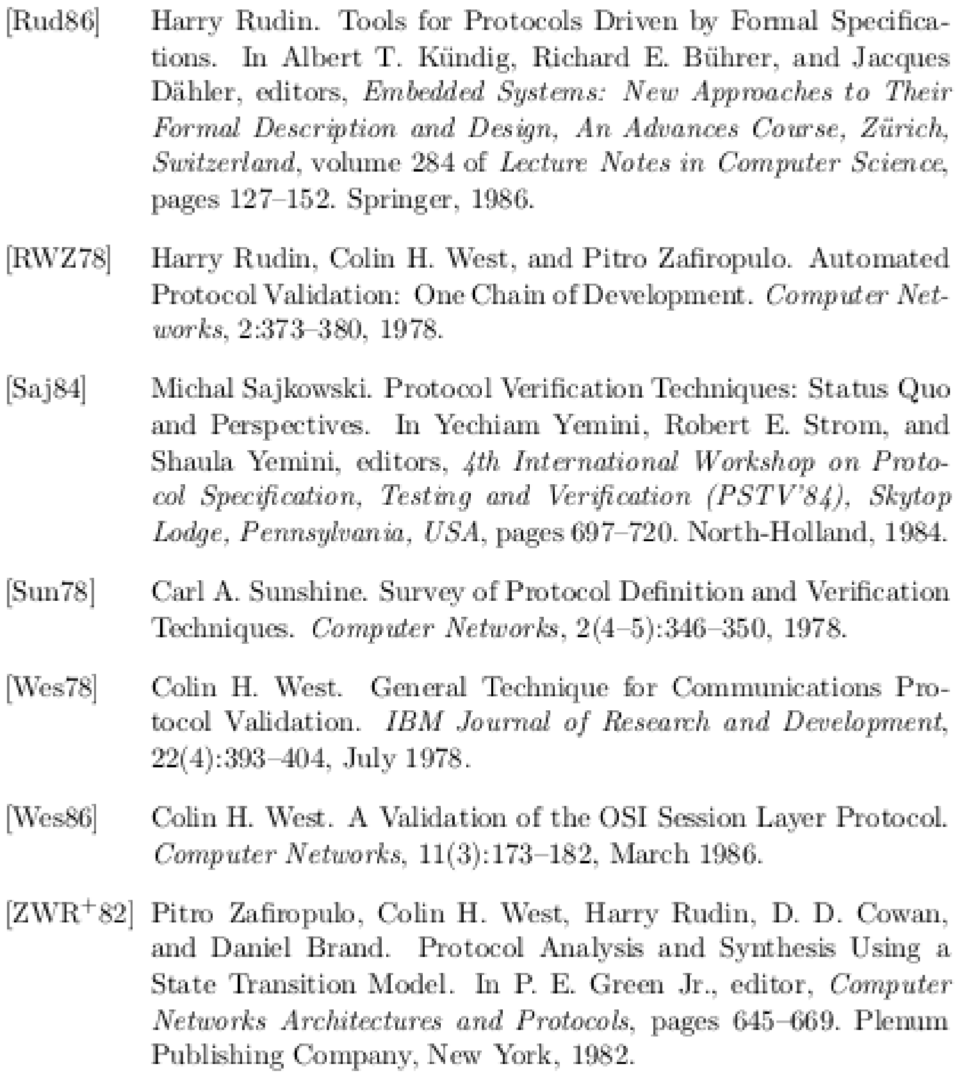
Fig. 2. The OSI session layer validation system.

Formal analysis of the (slightly simplified) OSI session layer protocol, using finite state machines communicating by bounded FIFO queues

Verification using automated protocol validation techniques based on state space exploration.

Various errors found and reported to ISO

[1986]



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1987

[Graf-Richier-Rodriguez-Sifakis-Voiron]

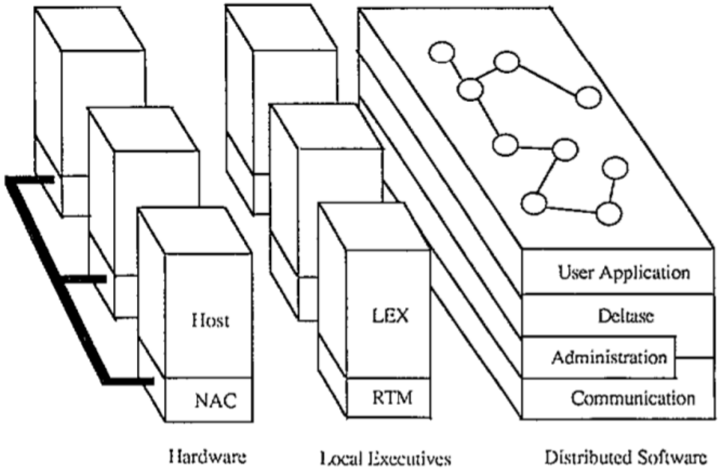
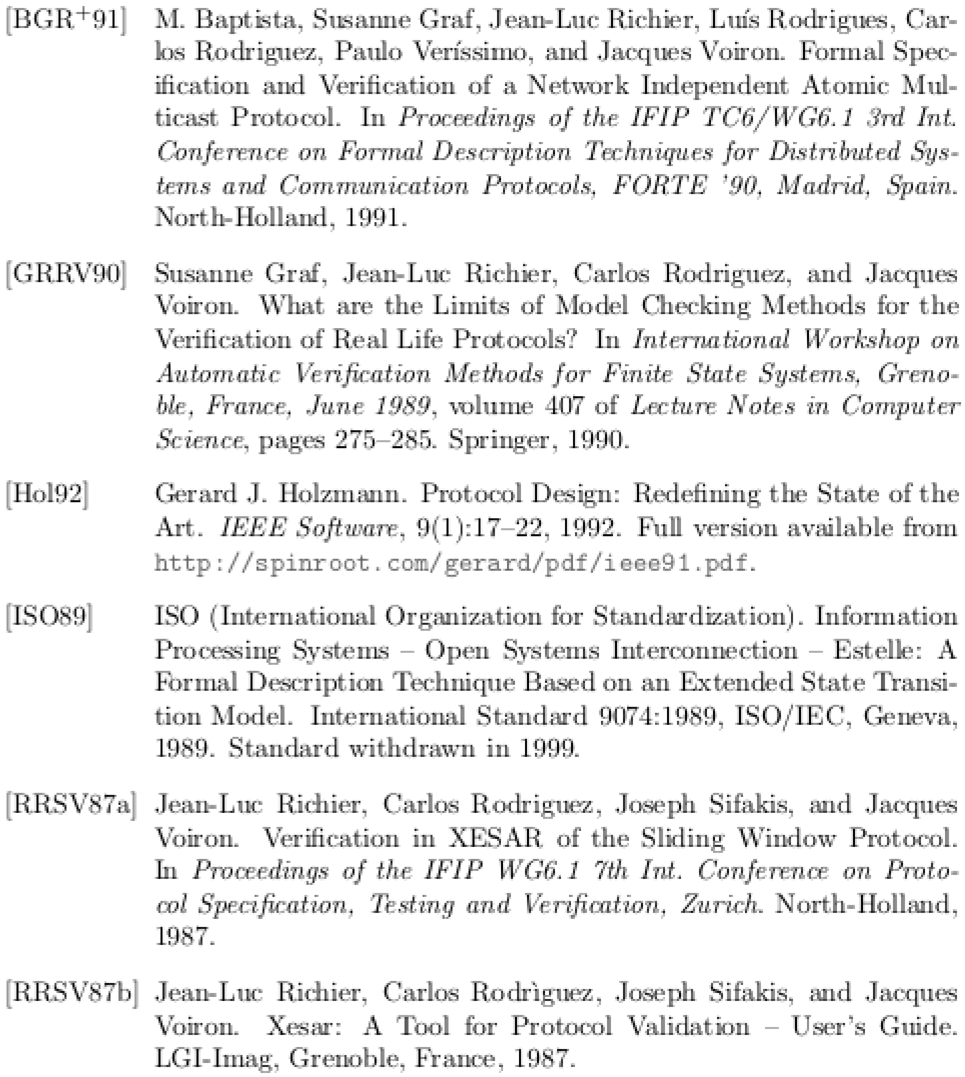


Figure 1. Abstract view of the Delta-4 architecture.

Specification in Estelle/R (a rendezvous-based variant of the protocol description language Estelle) and verification using the Xesar model checker of two protocols:

- a generic sliding window protocol, later intensively studied by the computer-aided verification community under the name "bounded retransmission protocol"
- an atomic multicast protocol for the Delta-4 distributed dependable architecture

[1987]



[BGR+91] M. Baptista, Susanne Graf, Jean-Luc Richier, Luís Rodrigues, Carlos Rodriguez, Paulo Veríssimo, and Jacques Voiron. Formal Specification and Verification of a Network Independent Atomic Multicast Protocol. In *Proceedings of the IFIP TC6/WG6.1 3rd Int. Conference on Formal Description Techniques for Distributed Systems and Communication Protocols, FORTE '90, Madrid, Spain.* North-Holland, 1991.

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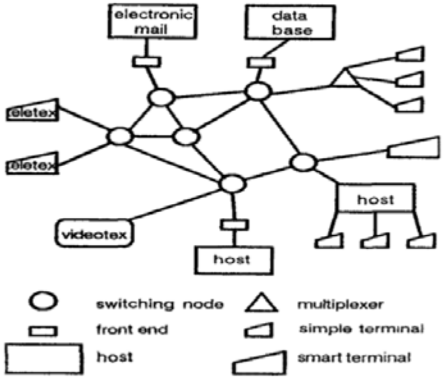
1988

[Ajubi-Aujla-Caneschi-Ferreira Pires-Freestone-Scollo-Turner-van de Heijden-van de Lagemaat-van Sinderen-Vissers-Widya]



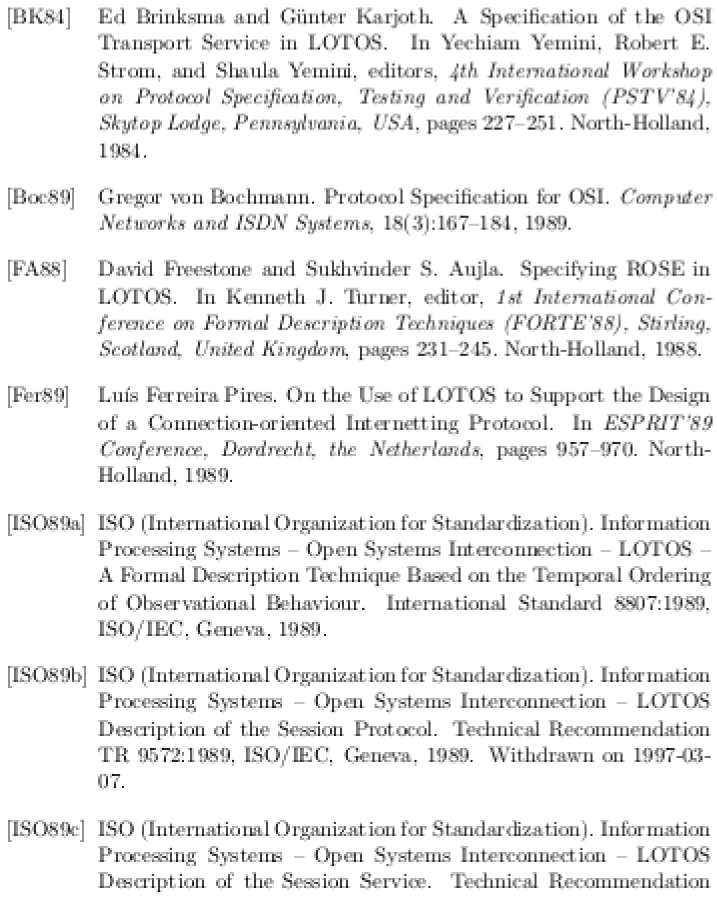
Configuration of an arbitrary OSI system.

Formal methods were used to specify OSI (Open System Interconnection) standards in a concise, unambiguous, implementation-neutral way.

LOTOS has been used intensively to specify :

- the service and protocol of the session layer
- the service and protocol of the transport layer
- the service and protocol of the network layer
- at the application layer
  - ROSE (Remote Operations Service Element) service
  - CCR (Commitment, Concurrency and Recovery) service and protocol
  - DTP (Distributed Transaction Processing) protocol

[1988]



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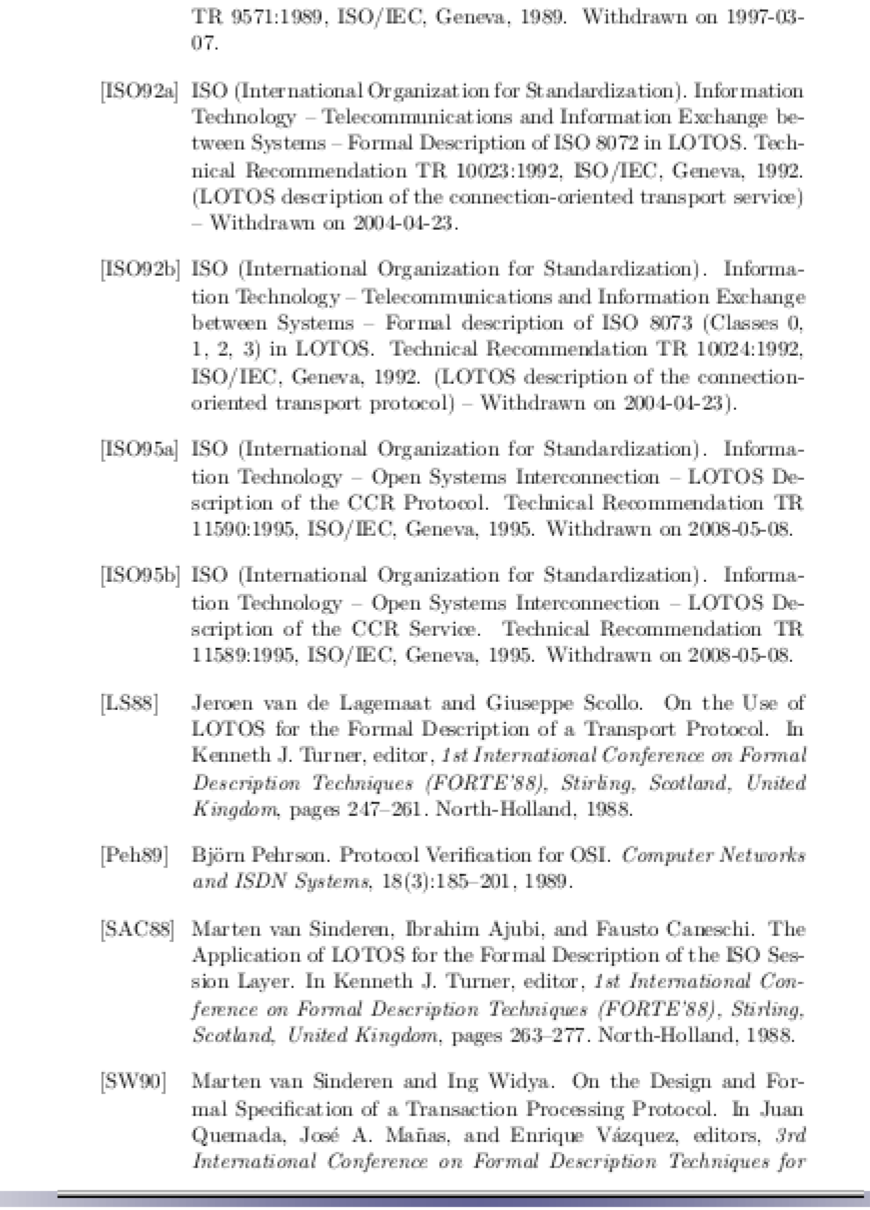
[ISO89c] ISO (International Organization for Standardization). Information Processing Systems – Open Systems Interconnection – LOTOS Description of the Session Service. Technical Recommendation

[1988]



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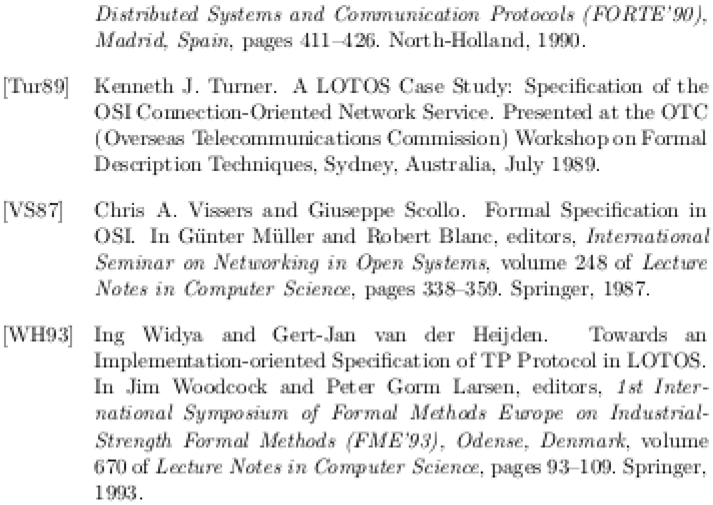
[1988]



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1989

[Stålmarck-Säflund-Borälv-Sheeran] [Groote-Koorn-Van Vlijmen] [Fokkink] [Eisner]

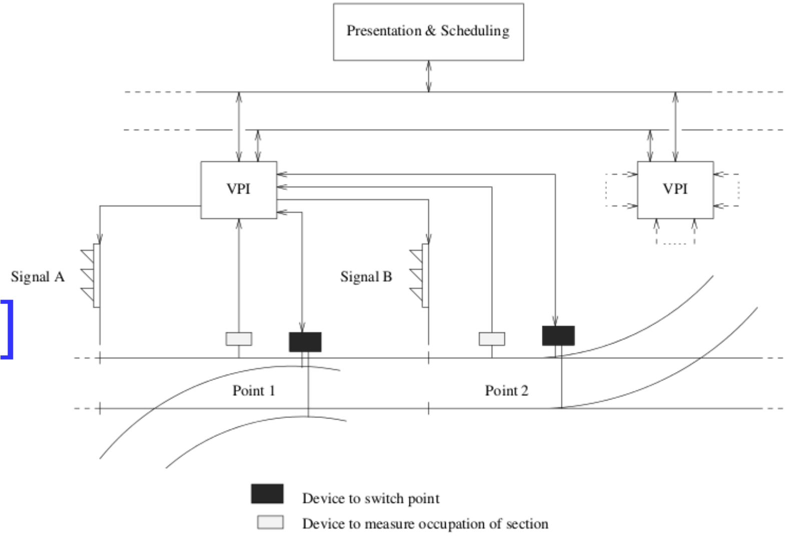
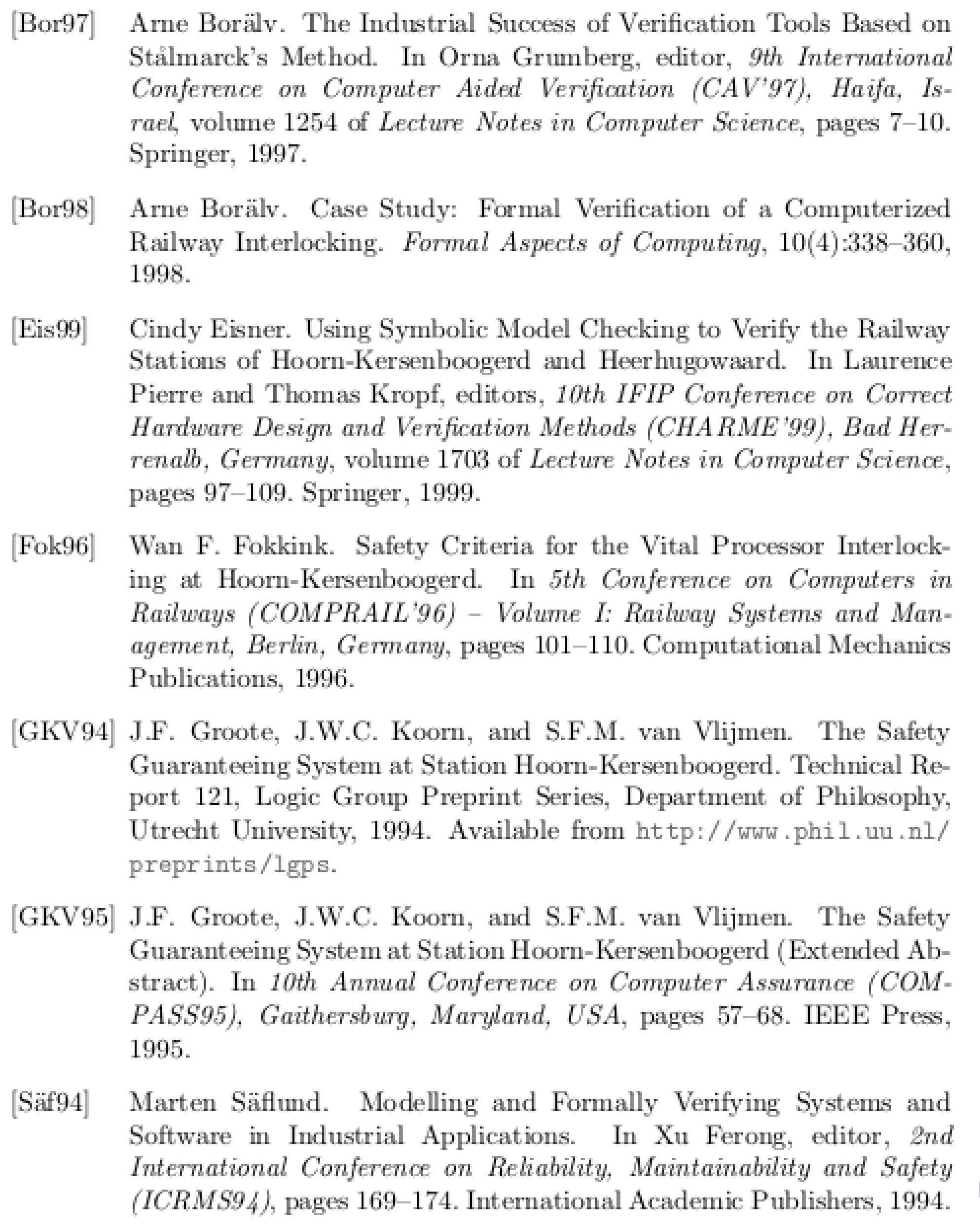

Presentation & Scheduling
VPI
VPI
Signal A
Signal B
Point 1
Point 2
■ Device to switch point
□ Device to measure occupation of section

Figure 1: VPIs and their environment

Formal verification, using a novel algorithm for efficiently proving large theorems of propositional logic, of safety-critical applications such as

- reverse flushing control in a nuclear plant's emergency cooling system
- landing gear control for a military aircraft
- railway signalling systems (interlocking verification)

[1989]



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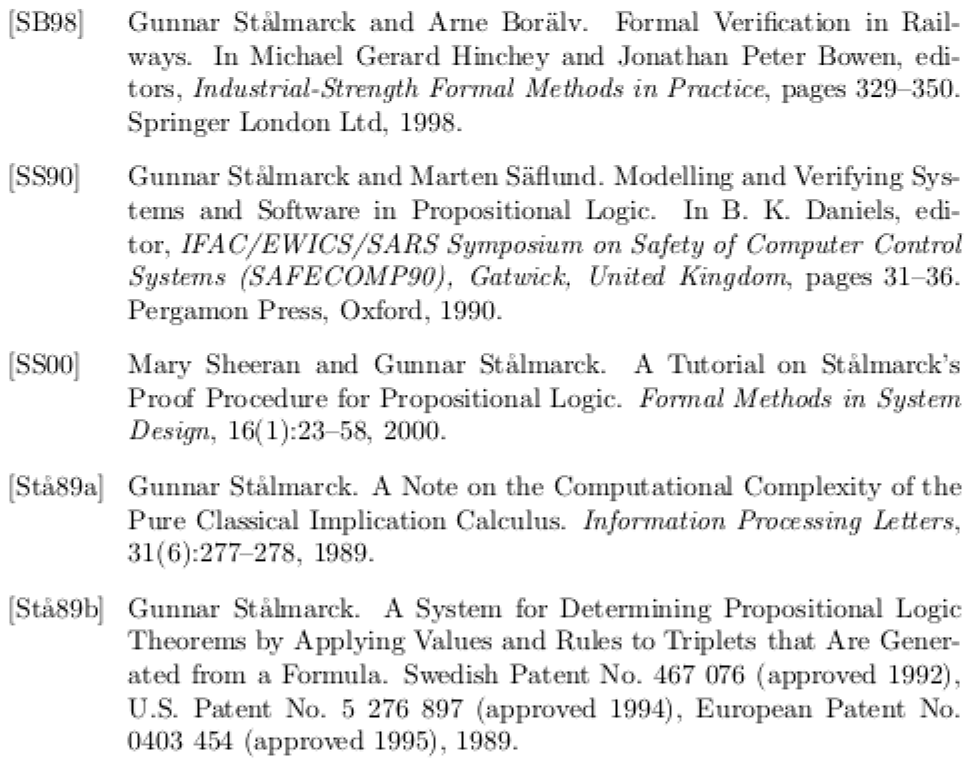
[1989]



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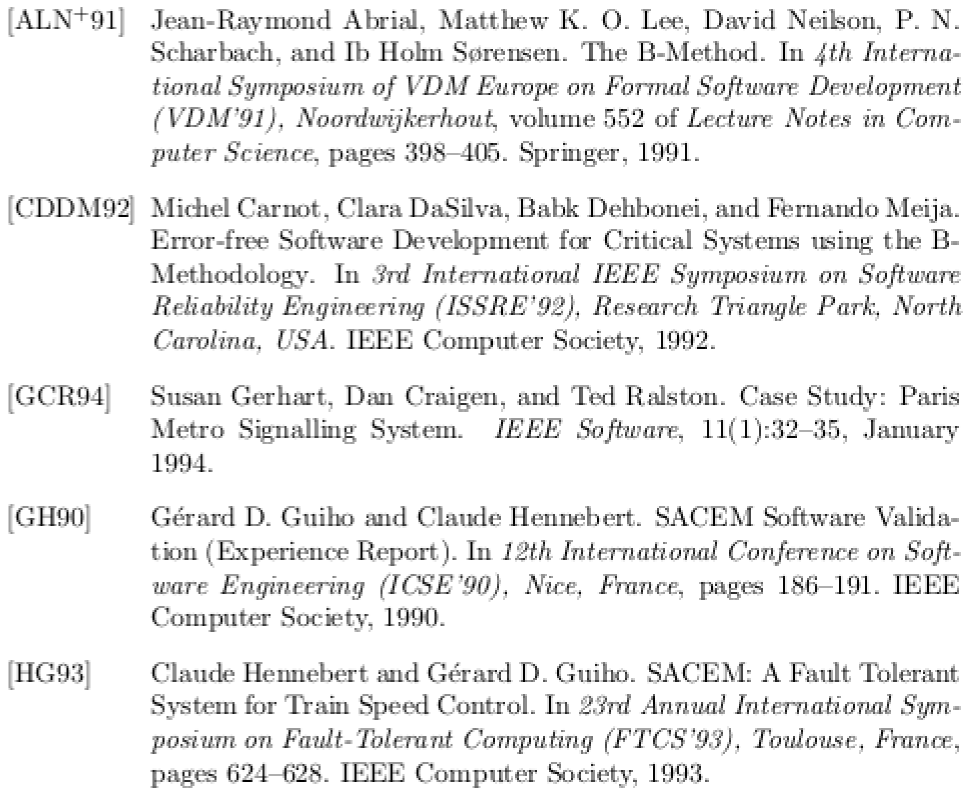
1990

[Guiho-Hennebert]

Formal specification using the B language and correctness proofs using Hoare-like logic (in addition to traditional code inspection and testing approaches) of SACEM, a fault-tolerant railway signalling system that controls train speed, signals drivers, and activates emergency brakes

SACEM was the first safety-critical software system certified by the French railway authority; it is used in Paris (800,000 passengers carried per day) and other cities in the world

[1990]



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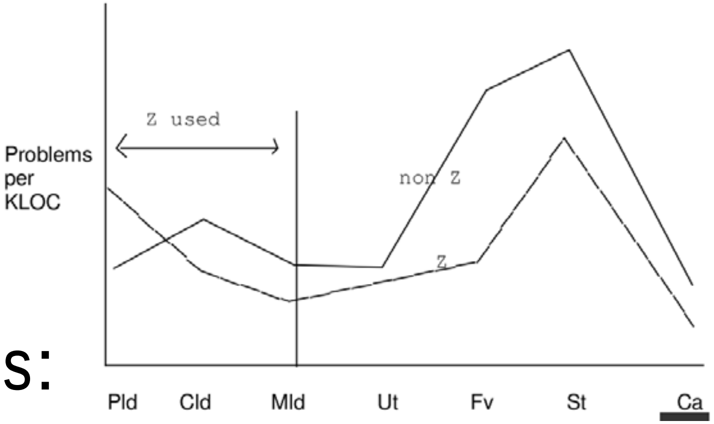
1991

[Houston-King]



Use of Z in two large IBM projects:

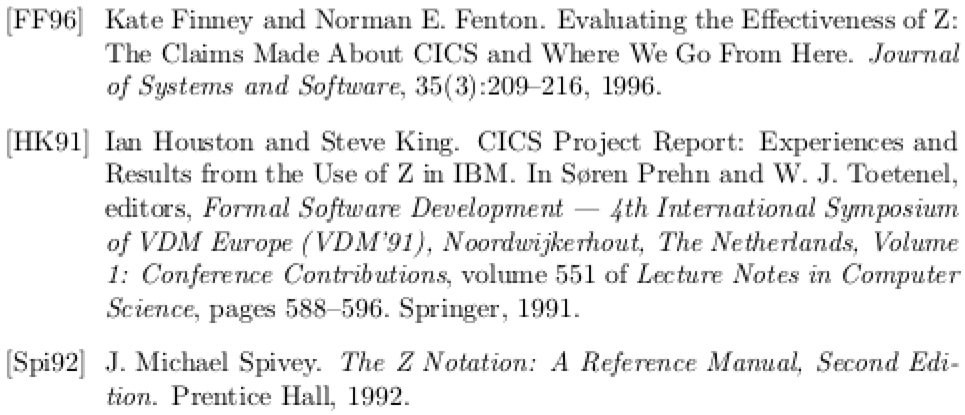
- a major new release IBM's CICS (Customer Information Control System) on-line transaction processing system
- the API (Application Programming Interface) of CICS.

Very few tools were used (only syntax and type checkers)

The authors report that the use of Z reduced the number of errors by a factor of 2.5 and saved 9% of the total development cost

But the significance of these conclusions was questioned later [Finney-Fenton]

[1991]



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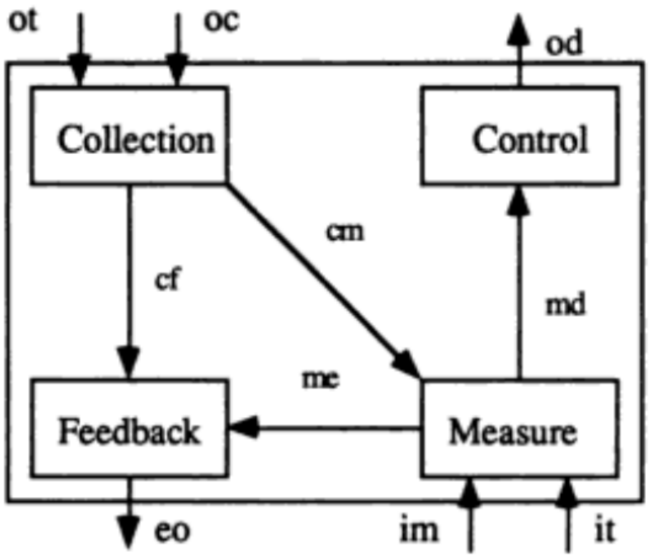
1992

[Paterno-Faconti] + [Duke-Harrison-Fornari-Mezzanotte-Sciacchitano-Löwgren] [Markopoulos]

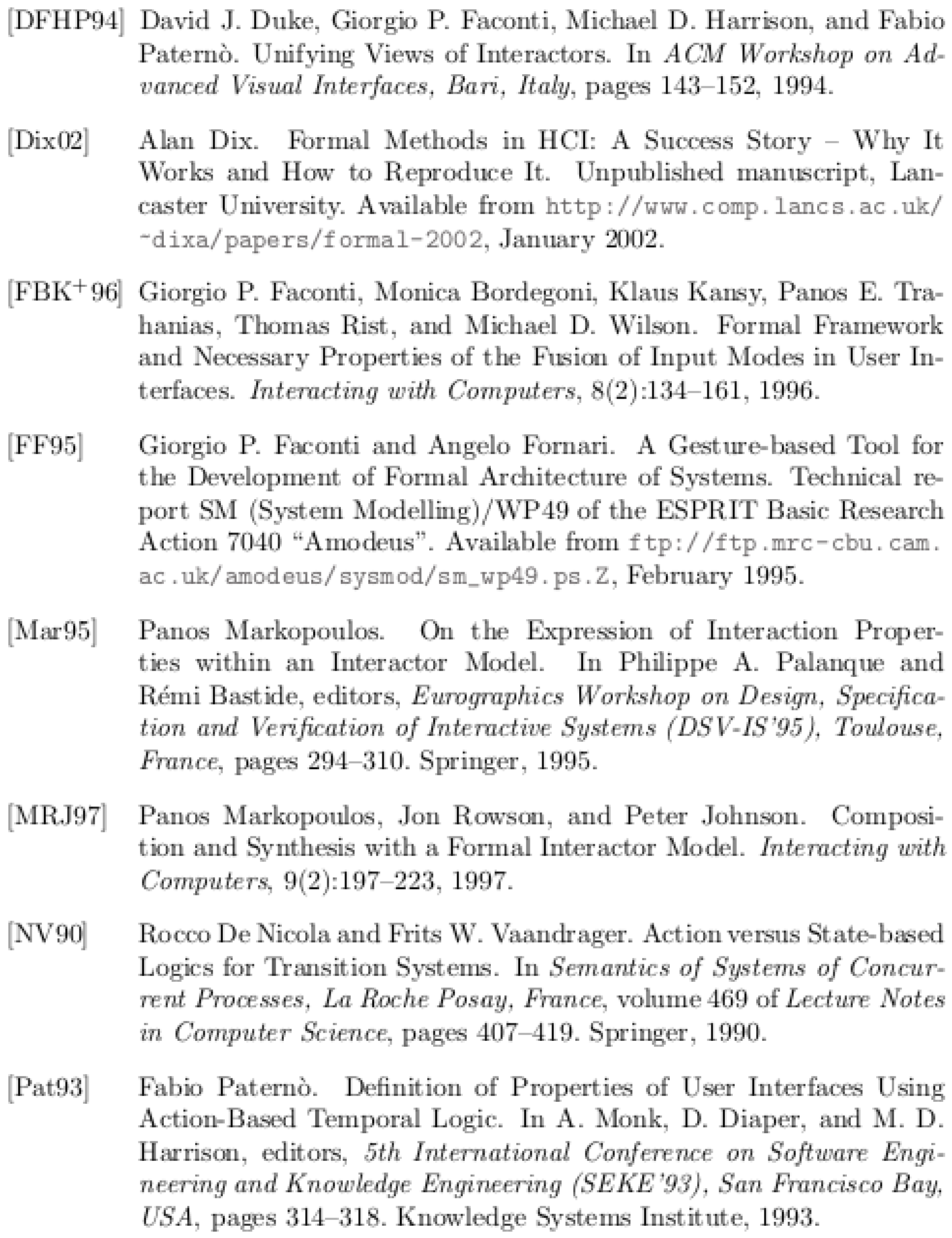


The Architecture of an Interactor

Formalization, using LOTOS and ACTL logic of the concept of "interactor", a software architectural model used to build complex user interface software

Several applications, e.g., MATIS, a multimodal interactive system enabling users to get information about flight schedules using speech, mouse and keyboard, or a combination of them

[1992]



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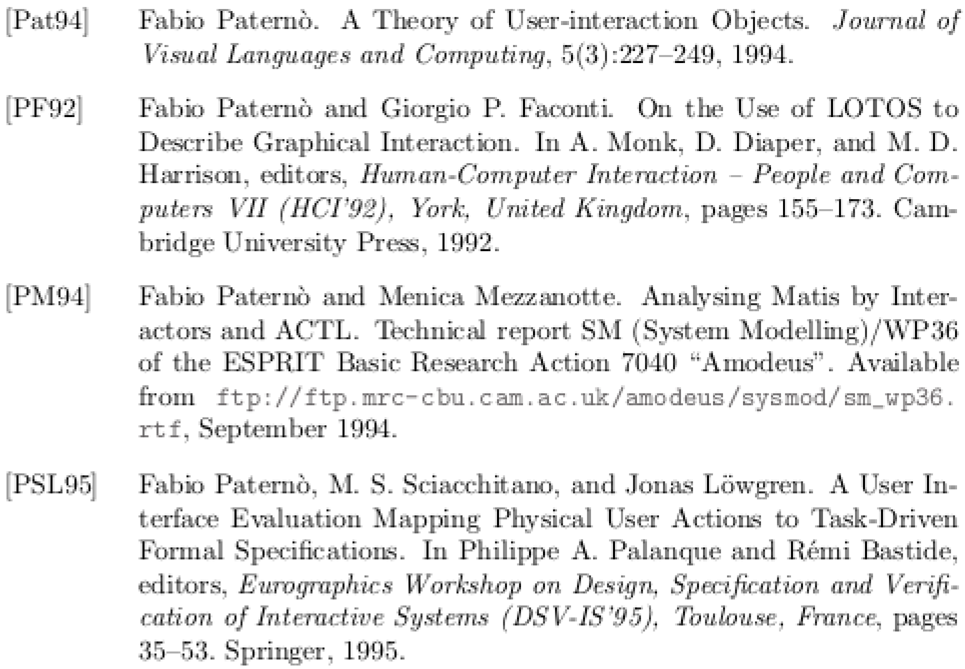
[1992]



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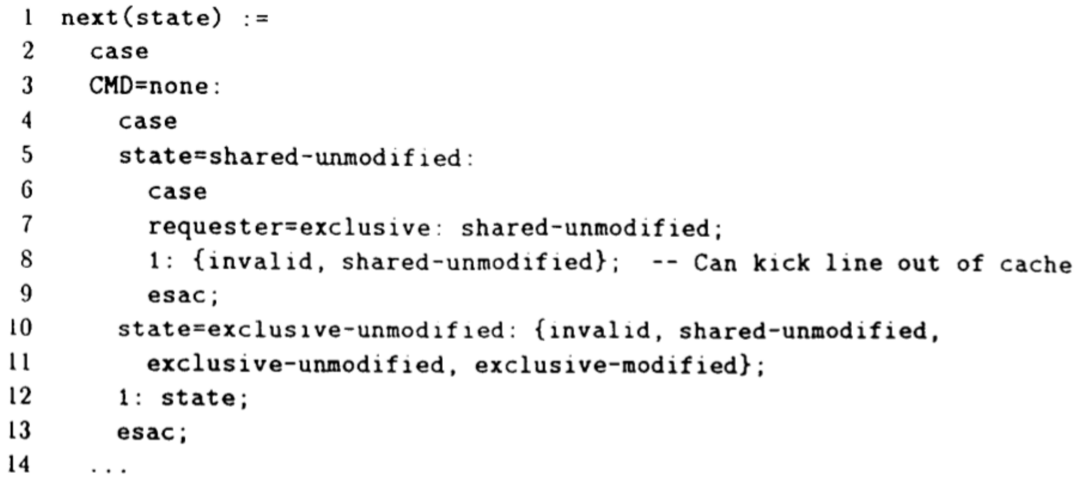
1993

[Clarke-Grumberg-Hiraishi-Jha-Long-McMillan-Ness]



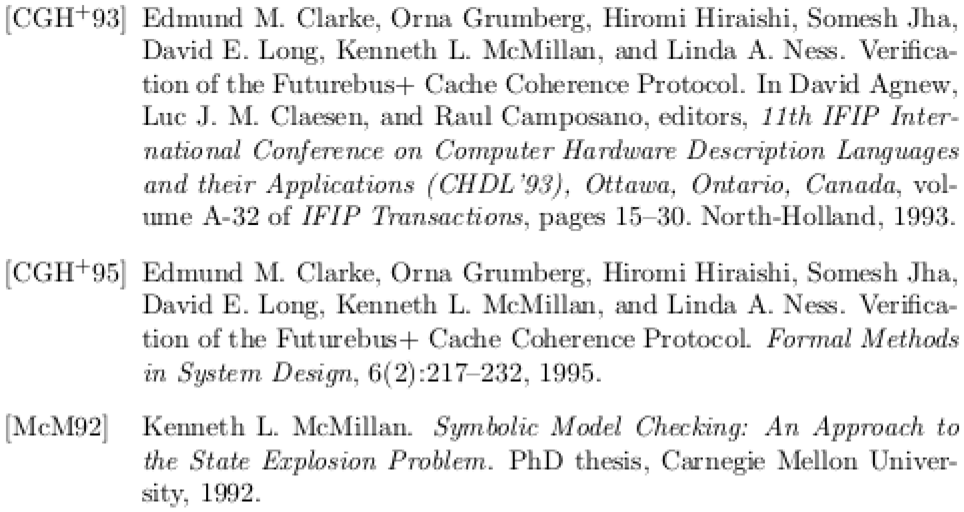
```
next(state) :=
  case
  CMD=none:
    case
    state=shared-unmodified:
      case
      requester=exclusive: shared-unmodified;
      1: {invalid, shared-unmodified};  -- Can kick line out of cache
      esac;
    state=exclusive-unmodified: {invalid, shared-unmodified,
      exclusive-unmodified, exclusive-modified};
    1: state;
    esac;
  ...
```

Formal specification and verification of the cache coherence protocol of IEEE standard 896.1-1991 "Futurebus+" using the SMV symbolic model checker

Several design errors previously undetected were found

First time that a formal verification tool was used to find errors in an IEEE standard

[1993]



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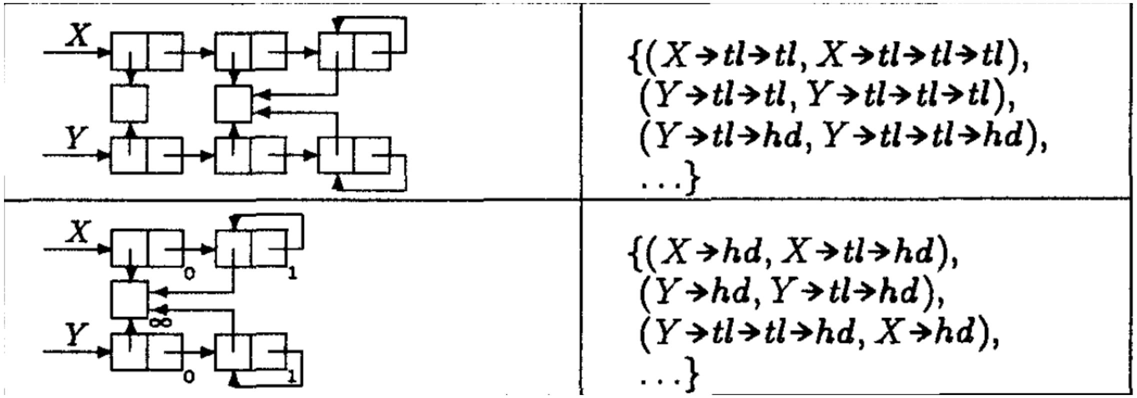
1994

[Andersen] [Deutsch] [Evans-Guttag-Horning-Tan]



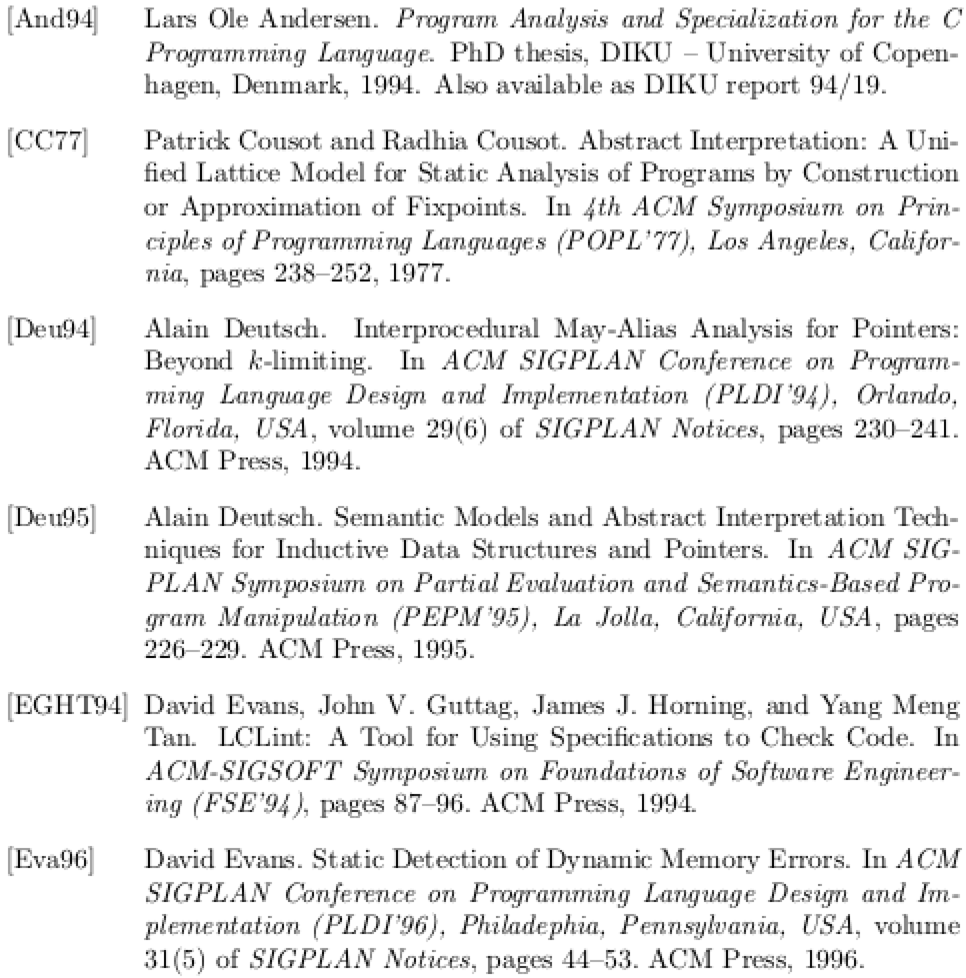
$\{(X\to tl\to tl,\ X\to tl\to tl\to tl),$
$(Y\to tl\to tl,\ Y\to tl\to tl\to tl),$
$(Y\to tl\to hd,\ Y\to tl\to tl\to hd),$
$\ldots\}$

$\{(X\to hd,\ X\to tl\to hd),$
$(Y\to hd,\ Y\to tl\to hd),$
$(Y\to tl\to tl\to hd,\ X\to hd),$
$\ldots\}$

Applications of the abstract interpretation to build static analyzers for C programs:

- LCLint annotation-assisted static checker (later extended to check dynamic memory allocation and buffer overflow vulnerabilities, and renamed into Splint)
- IABC static analysis tool for pointer manipulation and aliasing, which later went to marked under the name Polyspace Verifier

[1994]



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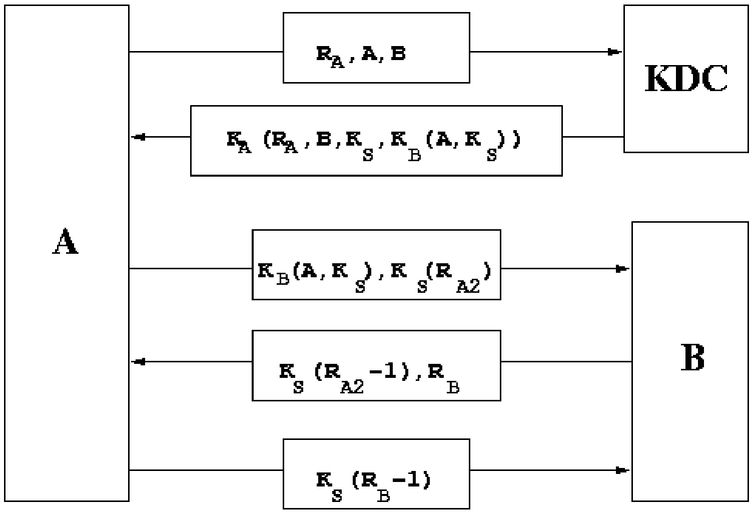
1995

[Lowe]

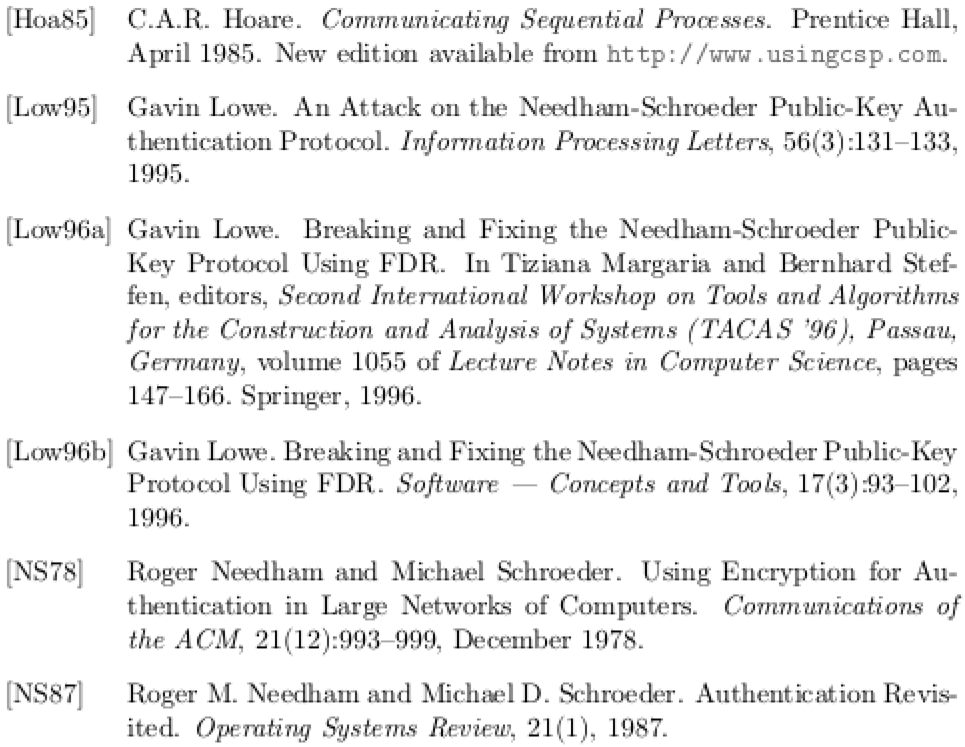


The Needham-Schroeder Authentication Protocol

Discovery, using CSP and FDR of an unknown, subtle "man-in-the-middle" attack in the classical Needham-Schroeder public-key protocol, which forms the basis of Kerberos authentication

This fueled a lot of research on formal methods and tools for the analysis of security protocols

[1995]



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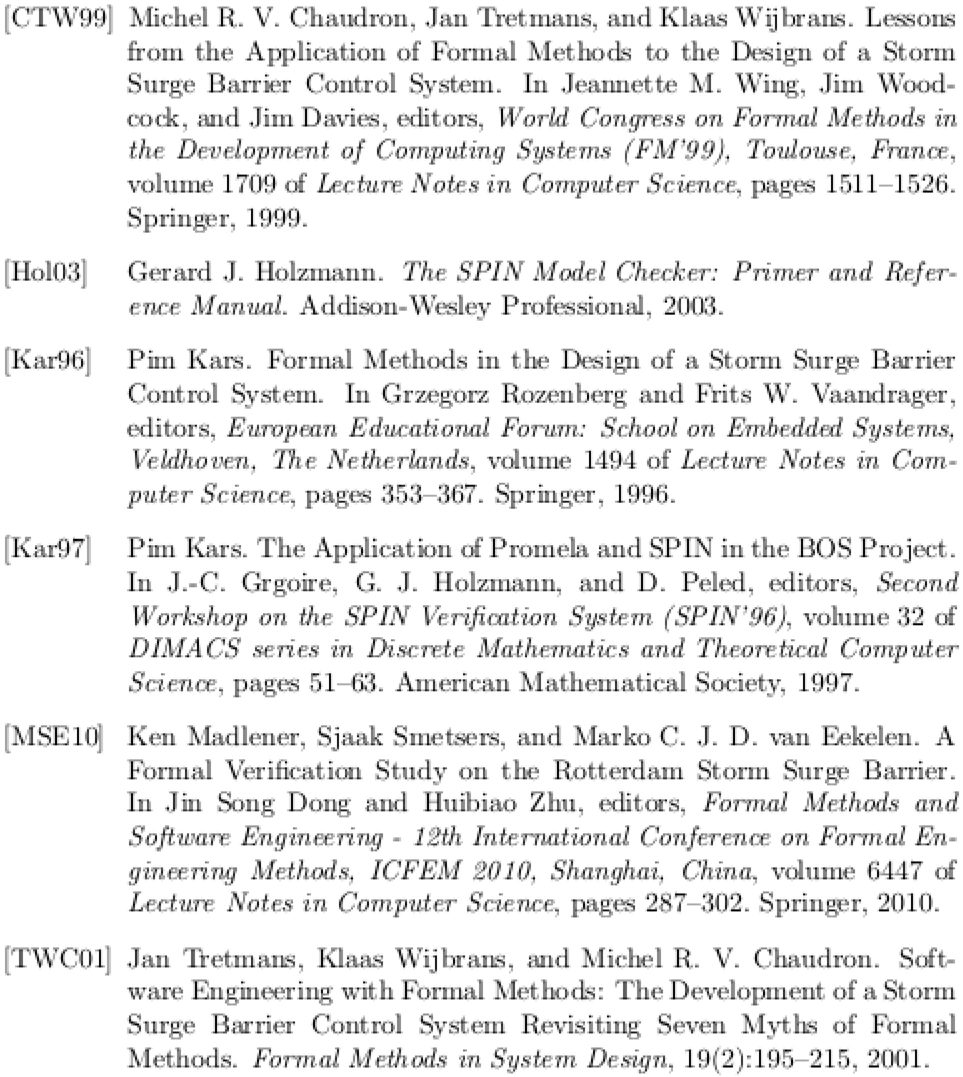
1996

[Kars] [Chaudron-Tretmans-Wijbrans] [Madlener-Smetsers-van Eekelen]

Specification using Z and Promela, and model checking using SPIN of the software controlling the storm surge barrier that protects Rotterdam from flooding, a life-critical application certified at the highest safety integrity level (SIL4)

[1996]



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1997

[Luttik]
[Kühne-Hooman-de Roever]
[Sighireanu-Mateescu]

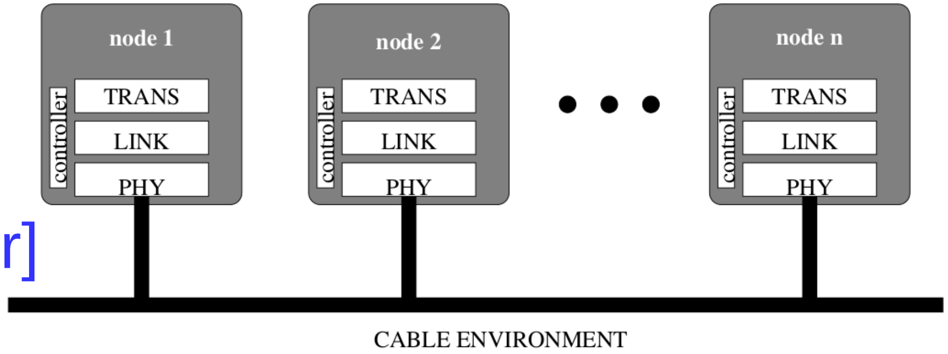


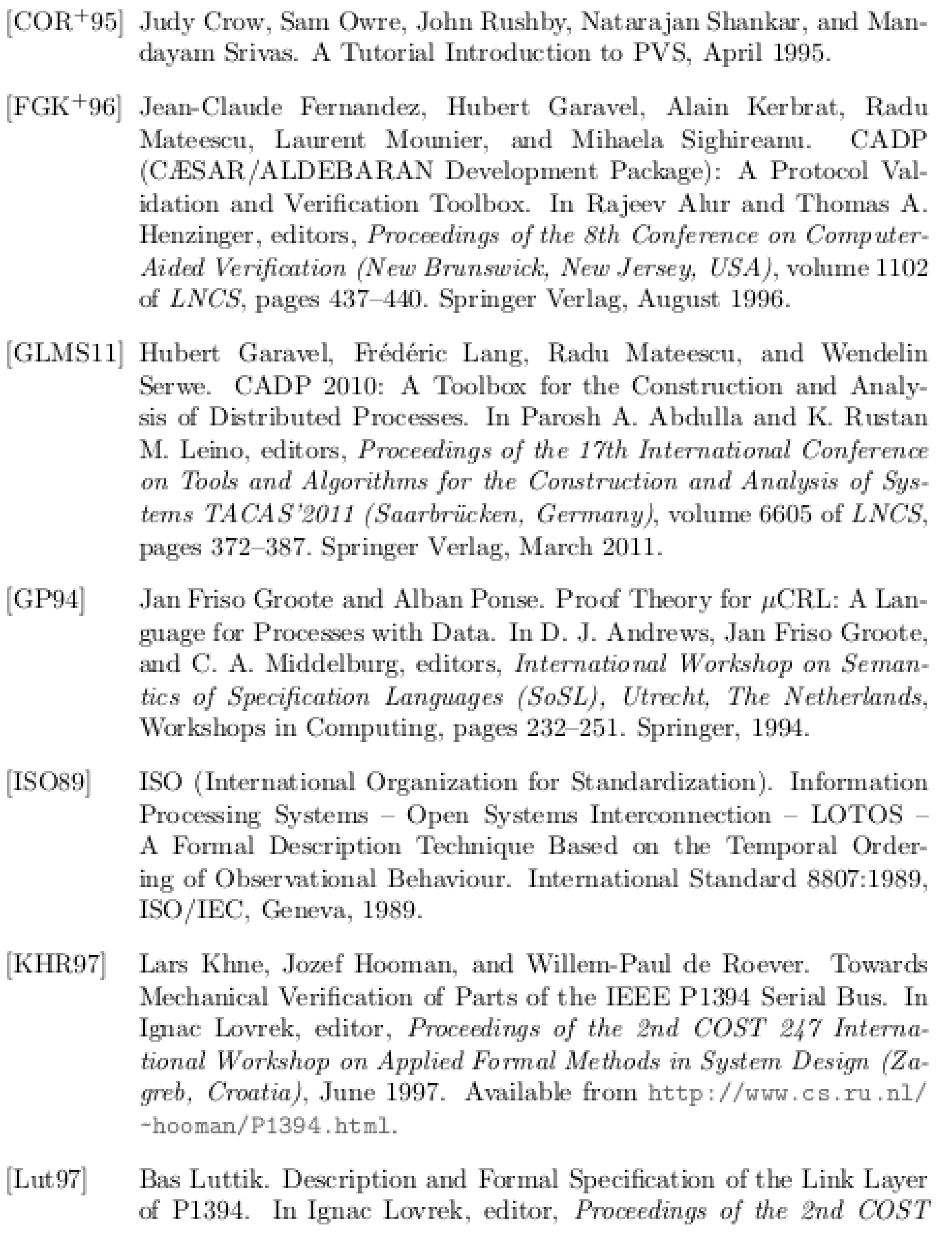
Figure 1: Serial Bus architecture.

Specification and analysis, using various formal methods, of the asynchronous mode of the Link Layer protocol of the IEEE Standard 1394 "Firewire" high-speed serial bus. Two problems found:

- a missing handling of pending requests discovered independently using PVS and μCRL
- a deadlock discovered using LOTOS and CADP in only one person.month without prior knowledge of the protocol

During the next decade, other IEEE 1394 protocols (root contention, tree identity, leader election, etc.) have been intensely scrutinized

[1997]



[COR+95] Judy Crow, Sam Owre, John Rushby, Natarajan Shankar, and Mandayam Srivas. A Tutorial Introduction to PVS, April 1995.

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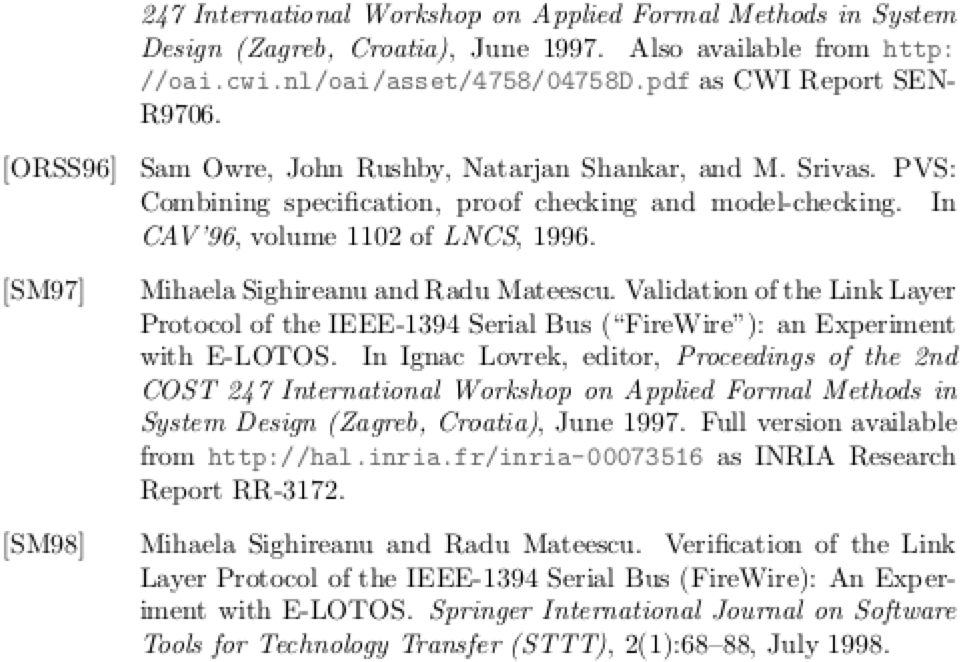
[1997]



247 International Workshop on Applied Formal Methods in System Design (Zagreb, Croatia), June 1997. Also available from http://oai.cwi.nl/oai/asset/4758/04758D.pdf as CWI Report SEN-R9706.

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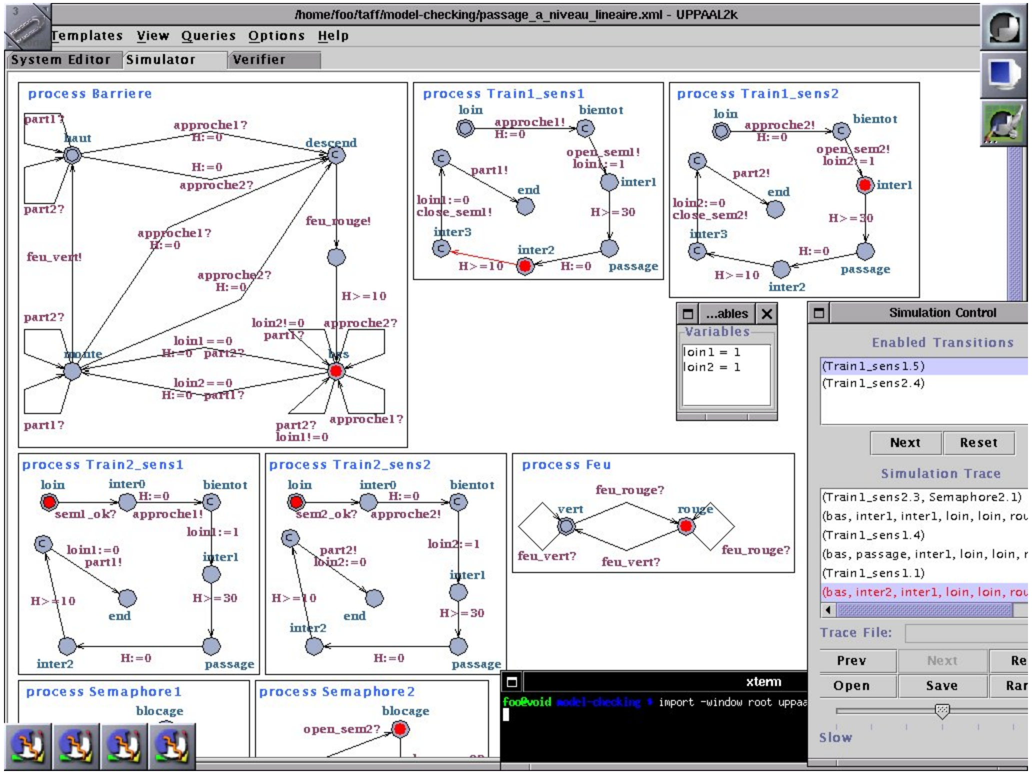
1998

[Bowman-Faconti-Katoen-Latella-Massink]
[Lindahl-Pettersson-Yi]
[Tripakis-Yovine]



```
loin1 = 1
loin2 = 1
```

```
(Train1_sens1.5)
(Train1_sens2.4)
```

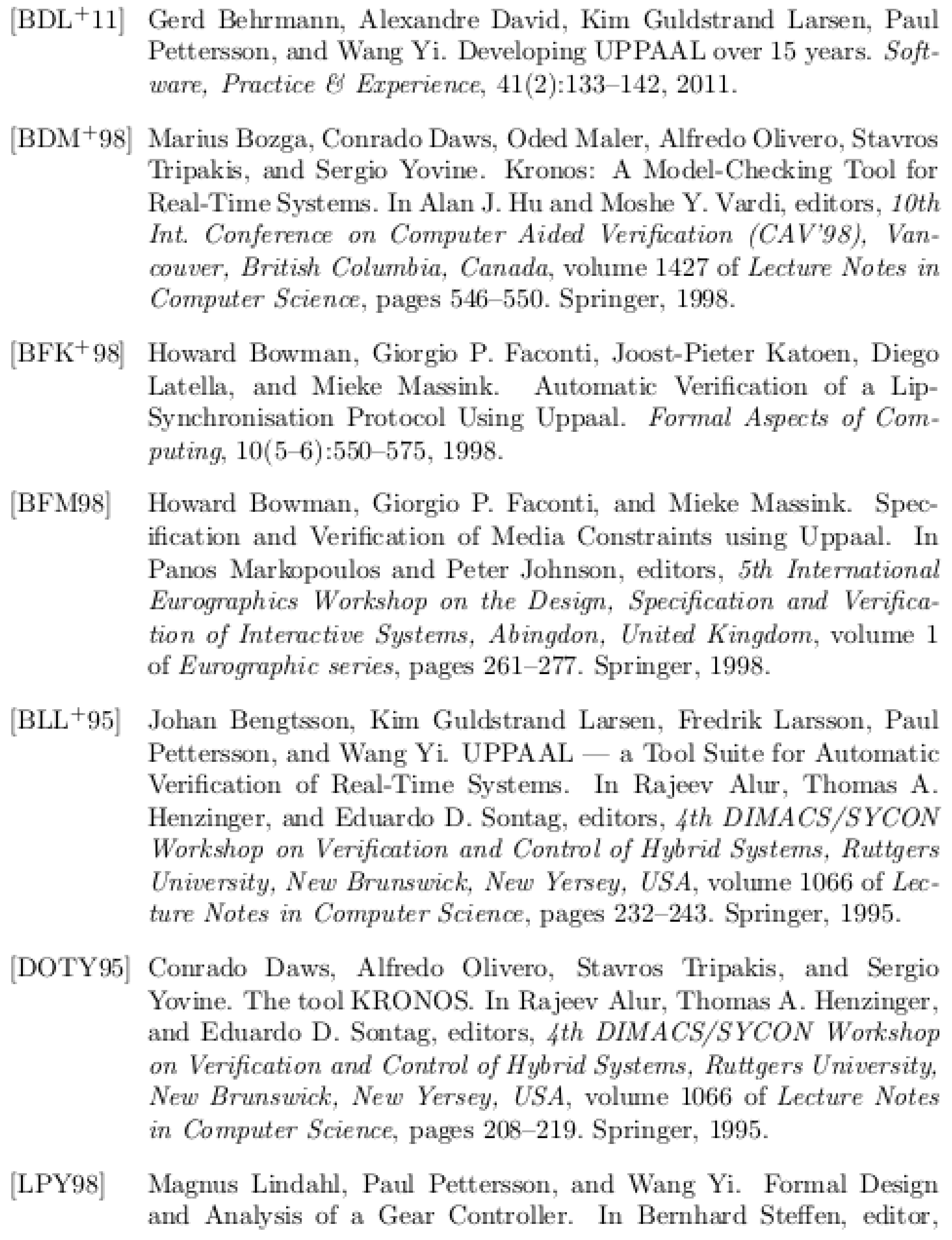
```
(Train1_sens2.3, Semaphore2.1)
(bas, inter1, inter1, loin, loin, rou
(Train1_sens1.4)
(bas, passage, inter1, loin, loin, r
(Train1_sens1.1)
(bas, inter2, inter1, loin, loin, rou
```

```
foo@void model-checking $ import -window root uppaa
```

Automated verification of several real-time protocols using:

- Kronos [Daws-Olivero-Tripakis-Yovine-Bozga-Maler]
- Uppaal [Bengtsson-Larsen-Larsson-Pettersson-Yi]

[1998]



[BDL+11] Gerd Behrmann, Alexandre David, Kim Guldstrand Larsen, Paul Pettersson, and Wang Yi. Developing UPPAAL over 15 years. *Software, Practice & Experience*, 41(2):133–142, 2011.

[BDM+98] Marius Bozga, Conrado Daws, Oded Maler, Alfredo Olivero, Stavros Tripakis, and Sergio Yovine. Kronos: A Model-Checking Tool for Real-Time Systems. In Alan J. Hu and Moshe Y. Vardi, editors, *10th Int. Conference on Computer Aided Verification (CAV'98), Vancouver, British Columbia, Canada*, volume 1427 of *Lecture Notes in Computer Science*, pages 546–550. Springer, 1998.

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[BLL+95] Johan Bengtsson, Kim Guldstrand Larsen, Fredrik Larsson, Paul Pettersson, and Wang Yi. UPPAAL — a Tool Suite for Automatic Verification of Real-Time Systems. In Rajeev Alur, Thomas A. Henzinger, and Eduardo D. Sontag, editors, *4th DIMACS/SYCON Workshop on Verification and Control of Hybrid Systems, Ruttgers University, New Brunswick, New Yersey, USA*, volume 1066 of *Lecture Notes in Computer Science*, pages 232–243. Springer, 1995.

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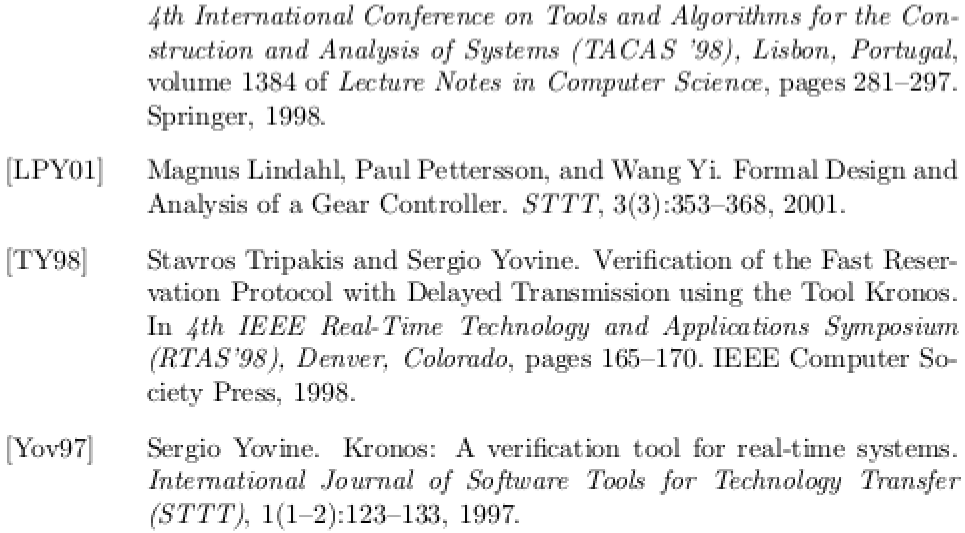
[LPY98] Magnus Lindahl, Paul Pettersson, and Wang Yi. Formal Design and Analysis of a Gear Controller. In Bernhard Steffen, editor,

[1998]



4th International Conference on Tools and Algorithms for the Construction and Analysis of Systems (TACAS '98), Lisbon, Portugal, volume 1384 of *Lecture Notes in Computer Science*, pages 281–297. Springer, 1998.

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1999

[Pfeifer-Schwier-von Henke-Rushby-Sorea-Steiner]

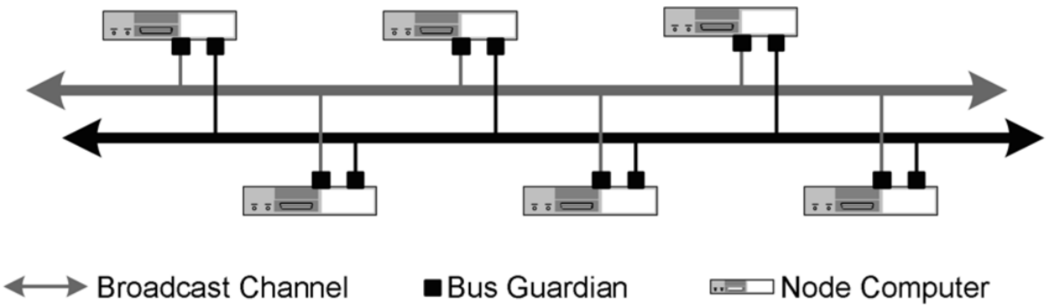


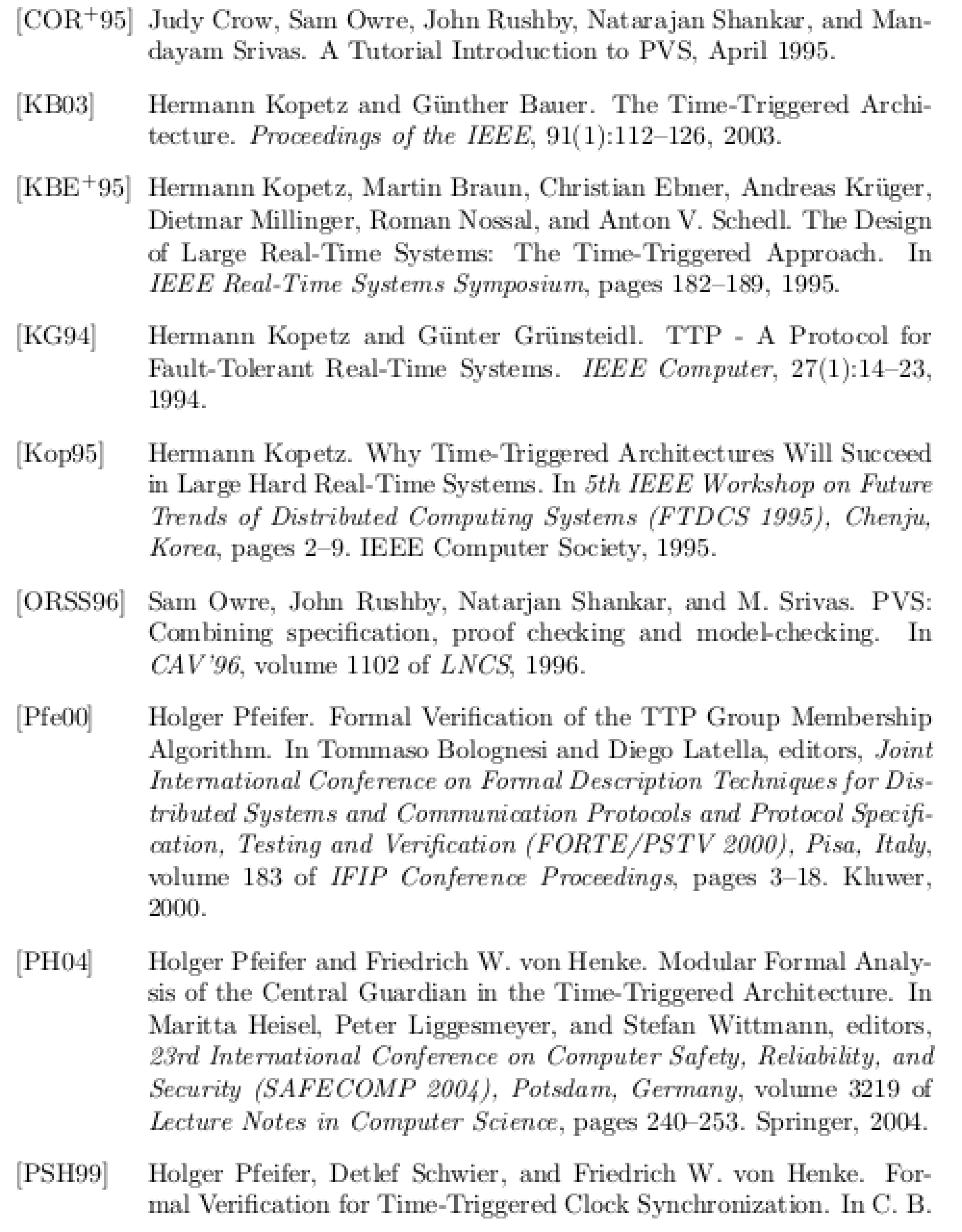
Fig. 5. Topology of TTA-bus

TTA (Time-Triggered Architecture) is a communication bus infrastructure guaranteeing dependability, predictability, and real-time requirements [Kopetz-Bauer-Braun-Gründsteidl-etc]

TTA and similar architectures are used for distributed-control safety-critical applications in automotive, aerospace, railways, industrial automation and process control, medical systems, etc.

Formal verification using PVS of several key protocols of TTA

[1999]



[COR+95] Judy Crow, Sam Owre, John Rushby, Natarajan Shankar, and Mandayam Srivas. A Tutorial Introduction to PVS, April 1995.

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[Kop95] Hermann Kopetz. Why Time-Triggered Architectures Will Succeed in Large Hard Real-Time Systems. In *5th IEEE Workshop on Future Trends of Distributed Computing Systems (FTDCS 1995), Chenju, Korea*, pages 2–9. IEEE Computer Society, 1995.

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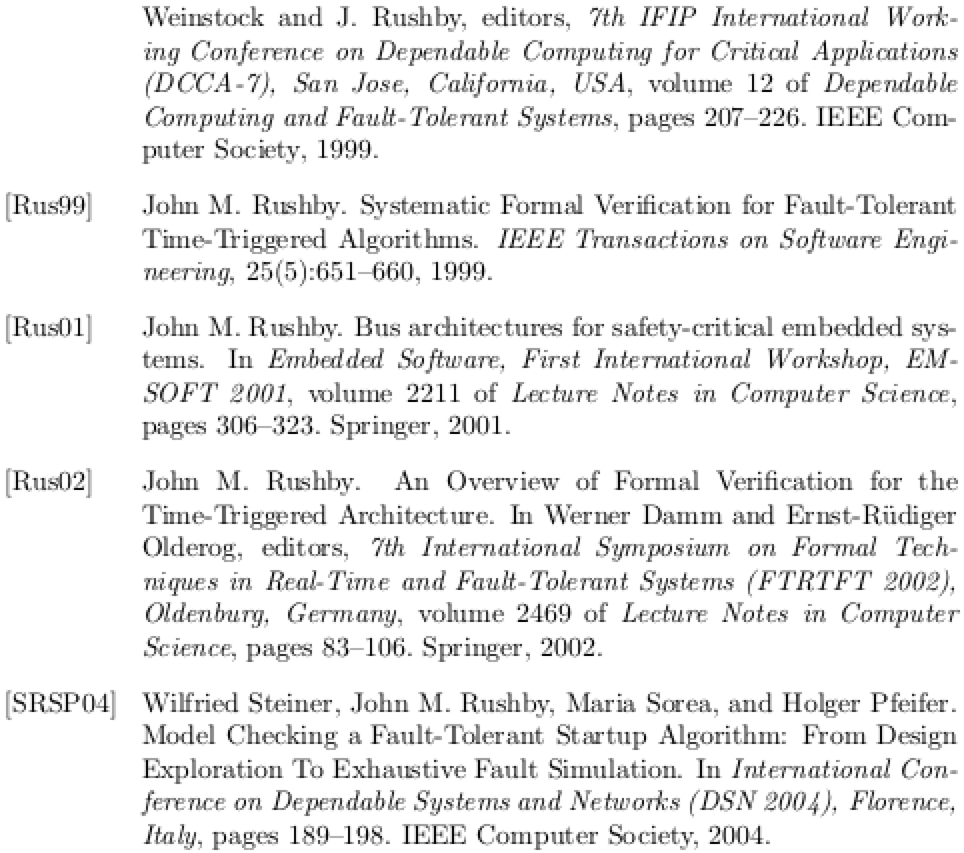

Weinstock and J. Rushby, editors, *7th IFIP International Working Conference on Dependable Computing for Critical Applications (DCCA-7), San Jose, California, USA*, volume 12 of *Dependable Computing and Fault-Tolerant Systems*, pages 207–226. IEEE Computer Society, 1999.

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[Rus02] John M. Rushby. An Overview of Formal Verification for the Time-Triggered Architecture. In Werner Damm and Ernst-Rüdiger Olderog, editors, *7th International Symposium on Formal Techniques in Real-Time and Fault-Tolerant Systems (FTRTFT 2002), Oldenburg, Germany*, volume 2469 of *Lecture Notes in Computer Science*, pages 83–106. Springer, 2002.

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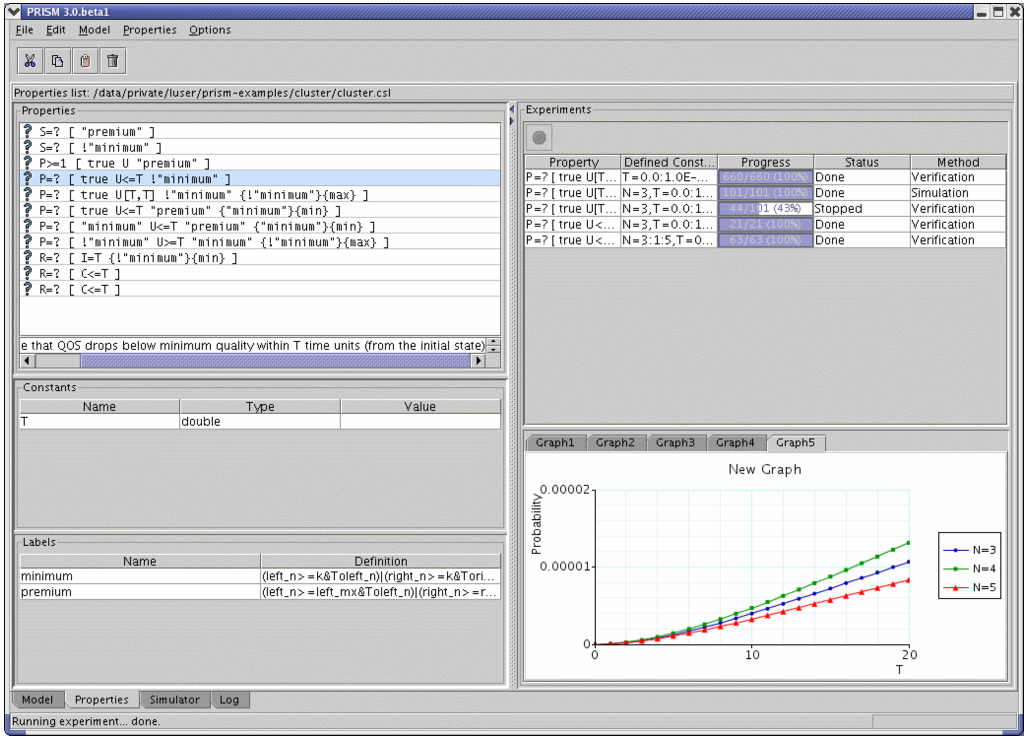
2000

[Kwiatkowska-Norman-Parker-Segala]


PRISM 3.0.beta1
File Edit Model Properties Options
Properties
Experiments
Graph1 Graph2 Graph3 Graph4 Graph5
New Graph
Probability
0.00002
0.00001
0
0
10
20
T
N=3
N=4
N=5
Model Properties Simulator Log

Properties list: /data/private/luser/prism-examples/cluster/cluster.csl

```
S=? [ "premium" ]
S=? [ !"minimum" ]
P>=1 [ true U "premium" ]
P=? [ true U<=T !"minimum" ]
P=? [ true U[T,T] !"minimum" {!"minimum"}{max} ]
P=? [ true U<=T "premium" {"minimum"}{min} ]
P=? [ "minimum" U<=T "premium" {"minimum"}{min} ]
P=? [ !"minimum" U>=T "minimum" {!"minimum"}{max} ]
R=? [ I=T {!"minimum"}{min} ]
R=? [ C<=T ]
R=? [ C<=T ]
```

e that QOS drops below minimum quality within T time units (from the initial state)

Constants

Name	Type	Value
T	double	

Labels

Name	Definition
minimum	(left_n>=k&Toleft_n)|(right_n>=k&Tori...
premium	(left_n>=left_mx&Toleft_n)|(right_n>=r...

Experiments

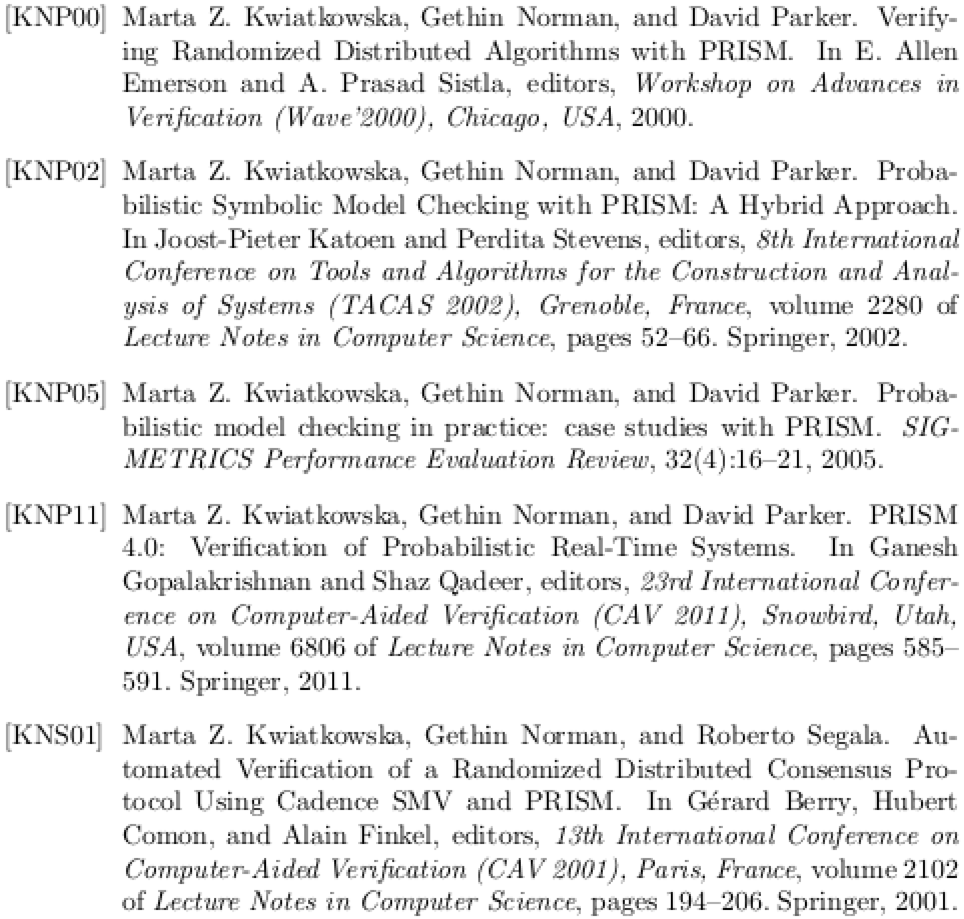
Property	Defined Const...	Progress	Status	Method
P=? [true U[T...	T=0.0:1.0E-...	660/660 (100%)	Done	Verification
P=? [true U[T...	N=3,T=0.0:1...	101/101 (100%)	Done	Simulation
P=? [true U[T...	N=3,T=0.0:1...	44/101 (43%)	Stopped	Verification
P=? [true U<...	N=3,T=0.0:1...	21/21 (100%)	Done	Verification
P=? [true U<...	N=3:1:5,T=0...	63/63 (100%)	Done	Verification

Running experiment... done.

Automated validation of several randomized distributed algorithms (taken from the literature) using the PRISM probabilistic model checker

PRISM has been used to analyze case studies in many different application domains

[2000]



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[KNP02] Marta Z. Kwiatkowska, Gethin Norman, and David Parker. Probabilistic Symbolic Model Checking with PRISM: A Hybrid Approach. In Joost-Pieter Katoen and Perdita Stevens, editors, *8th International Conference on Tools and Algorithms for the Construction and Analysis of Systems (TACAS 2002), Grenoble, France*, volume 2280 of *Lecture Notes in Computer Science*, pages 52–66. Springer, 2002.

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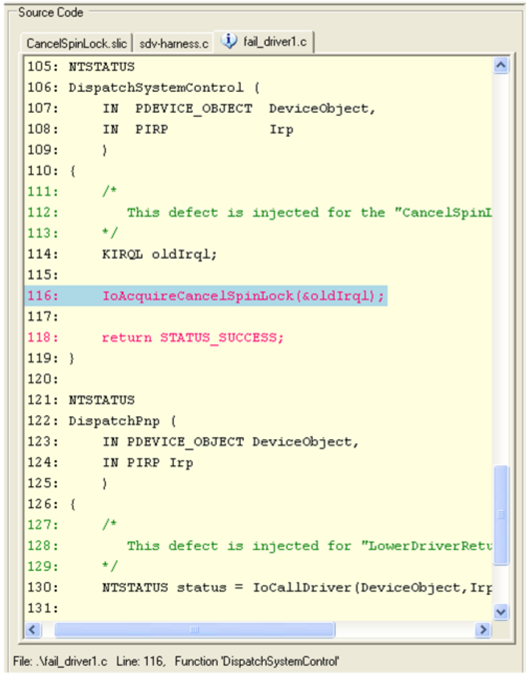
2001

[Ball-Bounimova-Chaki-Kumar-Levin-Lichtenberg-Rajamani]



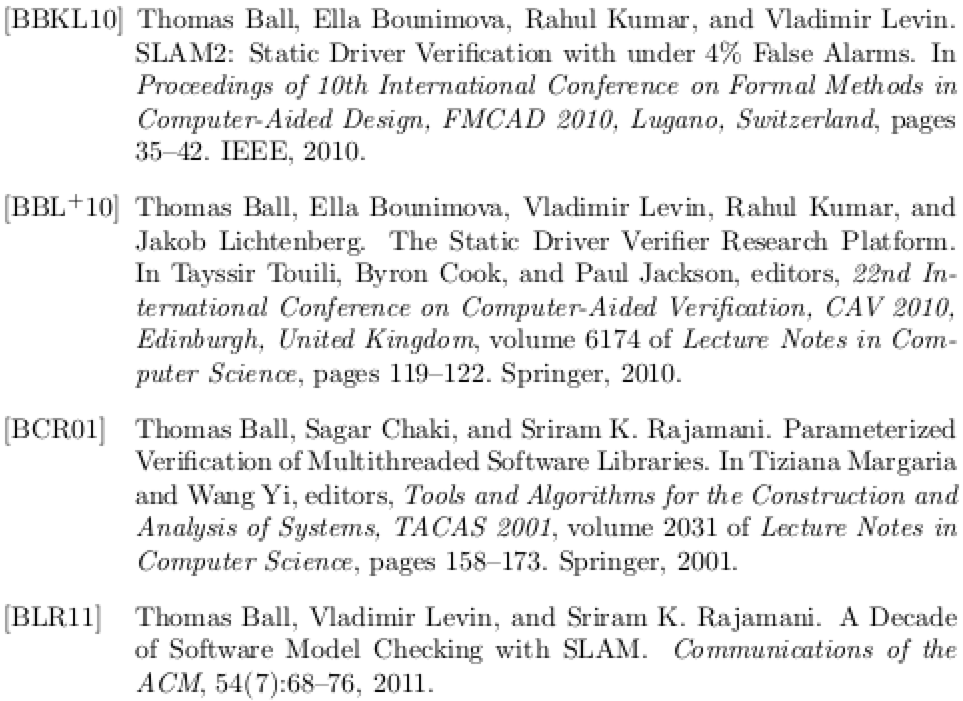
```
105: NTSTATUS
106: DispatchSystemControl (
107:     IN  PDEVICE_OBJECT  DeviceObject,
108:     IN  PIRP            Irp
109:     )
110: {
111:     /*
112:        This defect is injected for the "CancelSpinL
113:     */
114:     KIRQL oldIrql;
115:
116:     IoAcquireCancelSpinLock(&oldIrql);
117:
118:     return STATUS_SUCCESS;
119: }
120:
121: NTSTATUS
122: DispatchPnp (
123:     IN PDEVICE_OBJECT DeviceObject,
124:     IN PIRP Irp
125:     )
126: {
127:     /*
128:        This defect is injected for "LowerDriverRetu
129:     */
130:     NTSTATUS status = IoCallDriver(DeviceObject,Irp
131:
```

File: .\fail_driver1.c Line: 116, Function 'DispatchSystemControl'

Development of a verification platform (based on static analysis and symbolic model checking) for analyzing the source code of Microsoft Windows drivers (and more generally any source C code)

Check whether the invocations of API (Application Programming Interfaces) primitives obey rules for proper use

[2001]



[BBKL10] Thomas Ball, Ella Bounimova, Rahul Kumar, and Vladimir Levin. SLAM2: Static Driver Verification with under 4% False Alarms. In *Proceedings of 10th International Conference on Formal Methods in Computer-Aided Design, FMCAD 2010, Lugano, Switzerland*, pages 35–42. IEEE, 2010.

[BBL$^+$10] Thomas Ball, Ella Bounimova, Vladimir Levin, Rahul Kumar, and Jakob Lichtenberg. The Static Driver Verifier Research Platform. In Tayssir Touili, Byron Cook, and Paul Jackson, editors, *22nd International Conference on Computer-Aided Verification, CAV 2010, Edinburgh, United Kingdom*, volume 6174 of *Lecture Notes in Computer Science*, pages 119–122. Springer, 2010.

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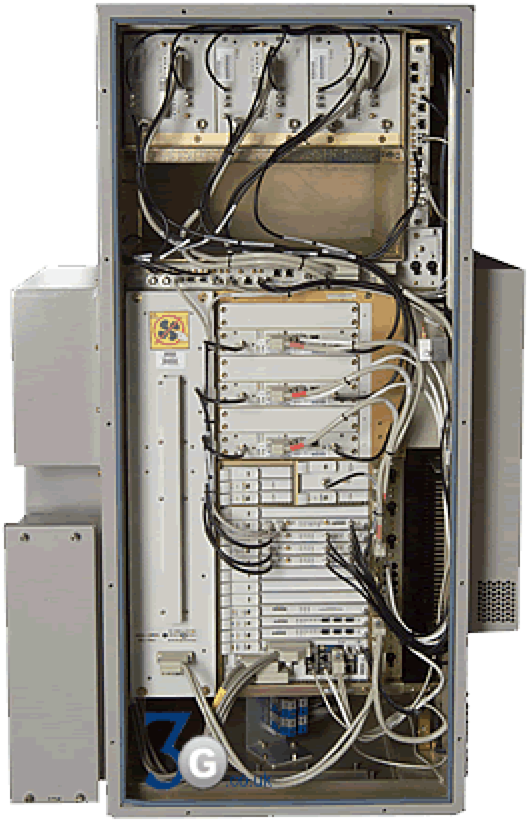
[BLR11] Thomas Ball, Vladimir Levin, and Sriram K. Rajamani. A Decade of Software Model Checking with SLAM. *Communications of the ACM*, 54(7):68–76, 2011.

2002

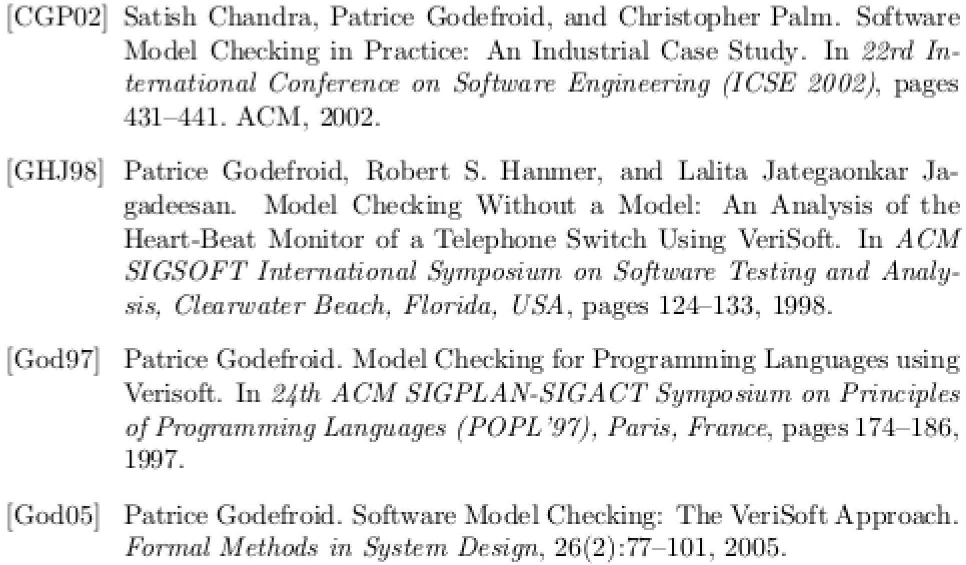
[Chandra-Godefroid-Palm]



Automated analysis of Lucent's CDMA base station call-processing software library (100,000s lines of C/C++ code) using the VeriSoft tool for systematic state space exploration

Detection of several critical bugs

[2002]



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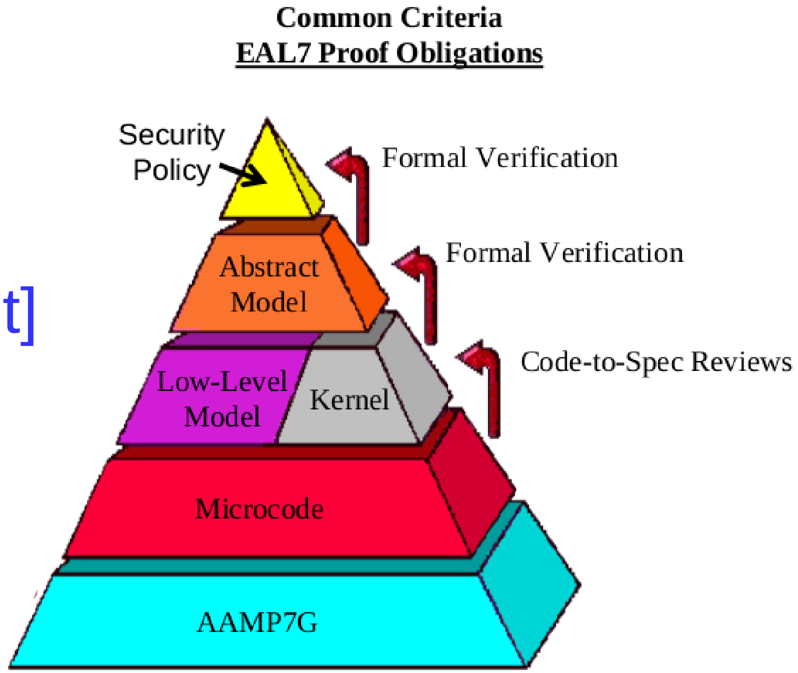
[God97] Patrice Godefroid. Model Checking for Programming Languages using Verisoft. In *24th ACM SIGPLAN-SIGACT Symposium on Principles of Programming Languages (POPL'97), Paris, France*, pages 174–186, 1997.

[God05] Patrice Godefroid. Software Model Checking: The VeriSoft Approach. *Formal Methods in System Design*, 26(2):77–101, 2005.

2003

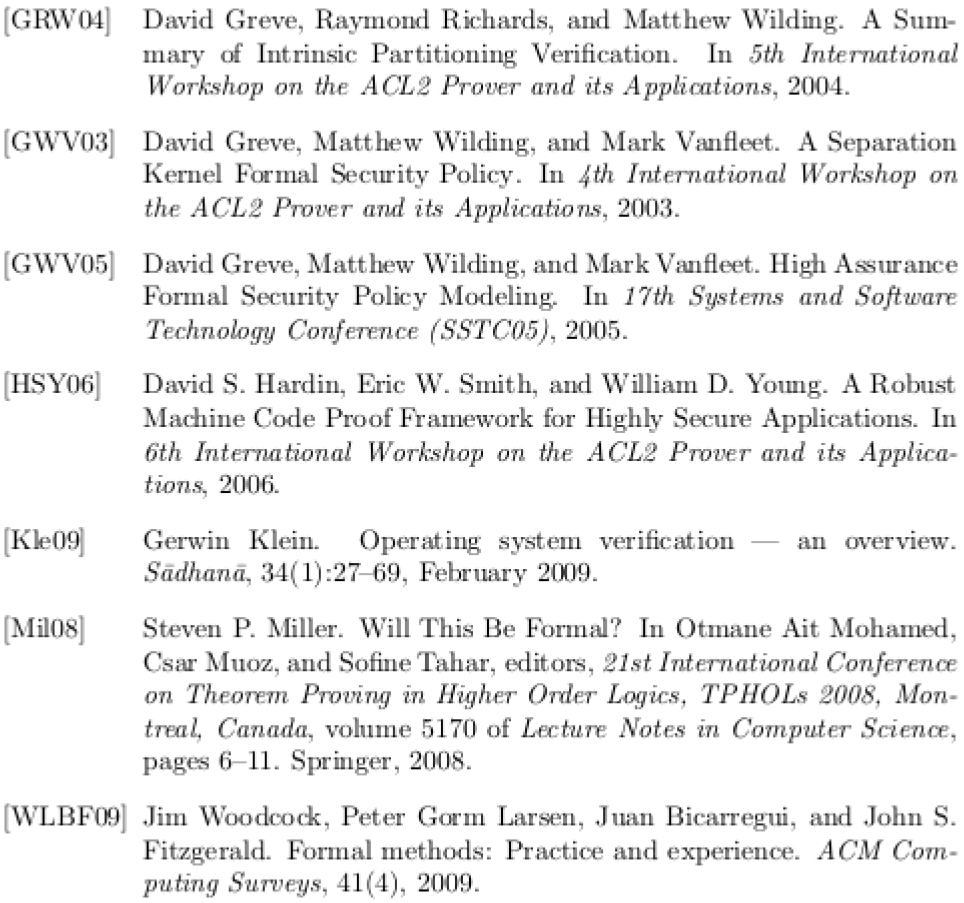
[Greve-Richards-Wilding-Vanfleet]
[Hardin-Smith-Young]



Formal proof using the ACL2 theorem prover that the microcode of the Rockwell Collins AAMP7 microprocessor respects a security policy corresponding to a static separation kernel

The microprocessor received a MILS Certificate from NSA to concurrently process Unclassified through Top Secret codeword information

[2003]



[GRW04] David Greve, Raymond Richards, and Matthew Wilding. A Summary of Intrinsic Partitioning Verification. In *5th International Workshop on the ACL2 Prover and its Applications*, 2004.

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[GWV05] David Greve, Matthew Wilding, and Mark Vanfleet. High Assurance Formal Security Policy Modeling. In *17th Systems and Software Technology Conference (SSTC05)*, 2005.

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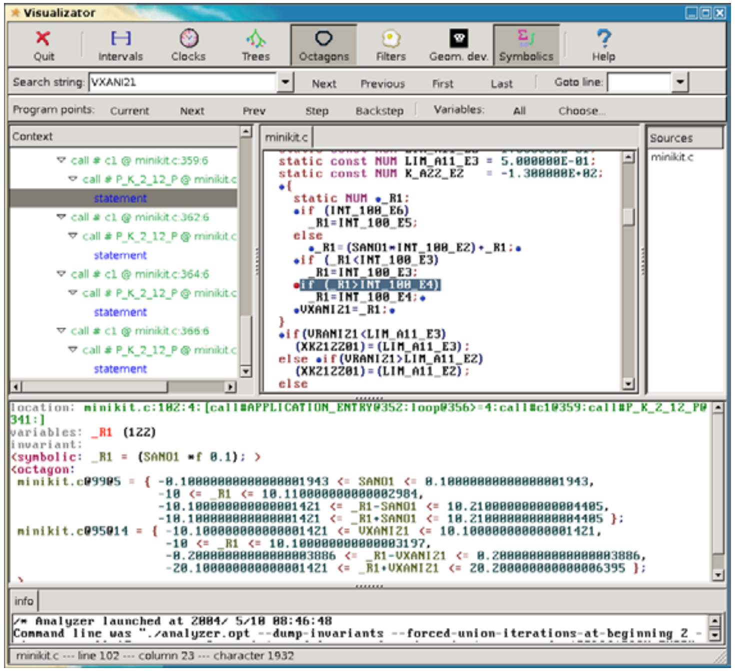
[Kle09] Gerwin Klein. Operating system verification — an overview. *Sādhanā*, 34(1):27–69, February 2009.

[Mil08] Steven P. Miller. Will This Be Formal? In Otmane Ait Mohamed, Csar Muoz, and Sofine Tahar, editors, *21st International Conference on Theorem Proving in Higher Order Logics, TPHOLs 2008, Montreal, Canada*, volume 5170 of *Lecture Notes in Computer Science*, pages 6–11. Springer, 2008.

[WLBF09] Jim Woodcock, Peter Gorm Larsen, Juan Bicarregui, and John S. Fitzgerald. Formal methods: Practice and experience. *ACM Computing Surveys*, 41(4), 2009.

2004

[Blanchet-Cousot-Cousot-Feret-Mauborgne-Miné-Monniaux-Rival] [Delmas-Sourys]



```
static const NUM LIM_A11_E3 = 5.000000E-01;
static const NUM K_A22_E2   = -1.300000E+02;
•{
  static NUM •_R1;
  •if (INT_100_E6)
    _R1=INT_100_E5;
  else
    •_R1=(SAN01*INT_100_E2)+_R1;•
  •if (_R1<INT_100_E3)
    _R1=INT_100_E3;
  •if (_R1>INT_100_E4)
    _R1=INT_100_E4;•
  •VXANI21=_R1;•
}
•if(VRANI21<LIM_A11_E3)
  (XK212Z01)=(LIM_A11_E3);
else •if(VRANI21>LIM_A11_E2)
  (XK212Z01)=(LIM_A11_E2);
else
```

```
location: minikit.c:102:4:[call#APPLICATION_ENTRY@352:loop@356>=4:call#c1@359:call#P_K_2_12_P@
341:]
variables: _R1 (122)
invariant:
<symbolic: _R1 = (SAN01 *f 0.1); >
<octagon:
 minikit.c@9905 = { -0.1000000000000001943 <= SAN01 <= 0.1000000000000001943,
                    -10 <= _R1 <= 10.110000000000002984,
                    -10.100000000000001421 <= _R1-SAN01 <= 10.210000000000004405,
                    -10.100000000000001421 <= _R1+SAN01 <= 10.210000000000004405 };
 minikit.c@95014 = { -10.100000000000001421 <= VXANI21 <= 10.100000000000001421,
                     -10 <= _R1 <= 10.100000000000003197,
                     -0.2000000000000003886 <= _R1-VXANI21 <= 0.2000000000000003886,
                     -20.100000000000001421 <= _R1+VXANI21 <= 20.200000000000006395 };
>
```

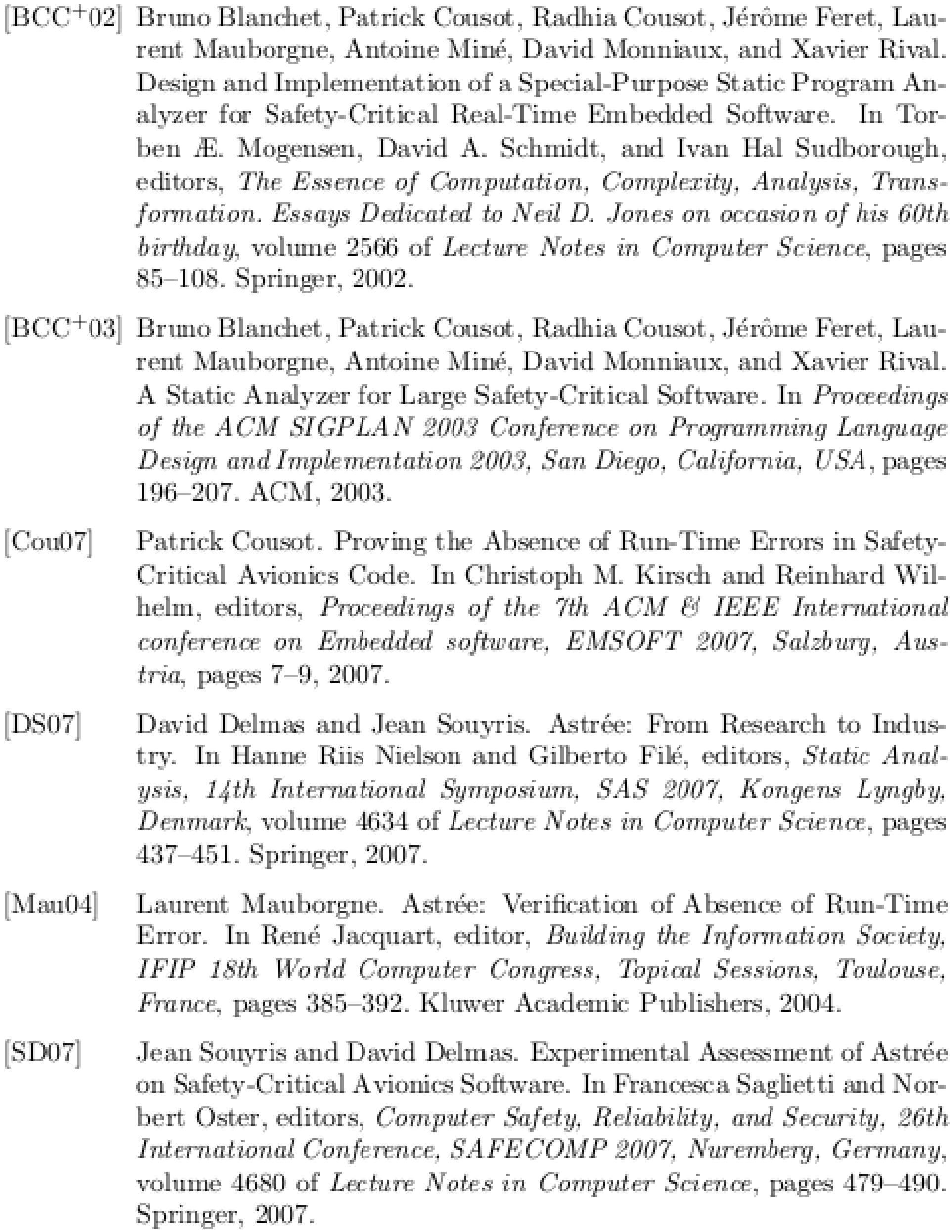
```
/* Analyzer launched at 2004/ 5/10 08:46:48
Command line was "./analyzer.opt --dump-invariants --forced-union-iterations-at-beginning 2 -
```

minikit.c --- line 102 --- column 23 --- character 1932

Proof, using the Astrée static analyzer based on abstract interpretation, of the absence of any run-time error in several safety-critical C programs of Airbus:

- primary flight-control software for the A340 fly-by-wire system
- electric flight-control codes for the A380 series

[2004]



[BCC+02] Bruno Blanchet, Patrick Cousot, Radhia Cousot, Jérôme Feret, Laurent Mauborgne, Antoine Miné, David Monniaux, and Xavier Rival. Design and Implementation of a Special-Purpose Static Program Analyzer for Safety-Critical Real-Time Embedded Software. In Torben Æ. Mogensen, David A. Schmidt, and Ivan Hal Sudborough, editors, *The Essence of Computation, Complexity, Analysis, Transformation. Essays Dedicated to Neil D. Jones on occasion of his 60th birthday*, volume 2566 of *Lecture Notes in Computer Science*, pages 85–108. Springer, 2002.

[BCC+03] Bruno Blanchet, Patrick Cousot, Radhia Cousot, Jérôme Feret, Laurent Mauborgne, Antoine Miné, David Monniaux, and Xavier Rival. A Static Analyzer for Large Safety-Critical Software. In *Proceedings of the ACM SIGPLAN 2003 Conference on Programming Language Design and Implementation 2003, San Diego, California, USA*, pages 196–207. ACM, 2003.

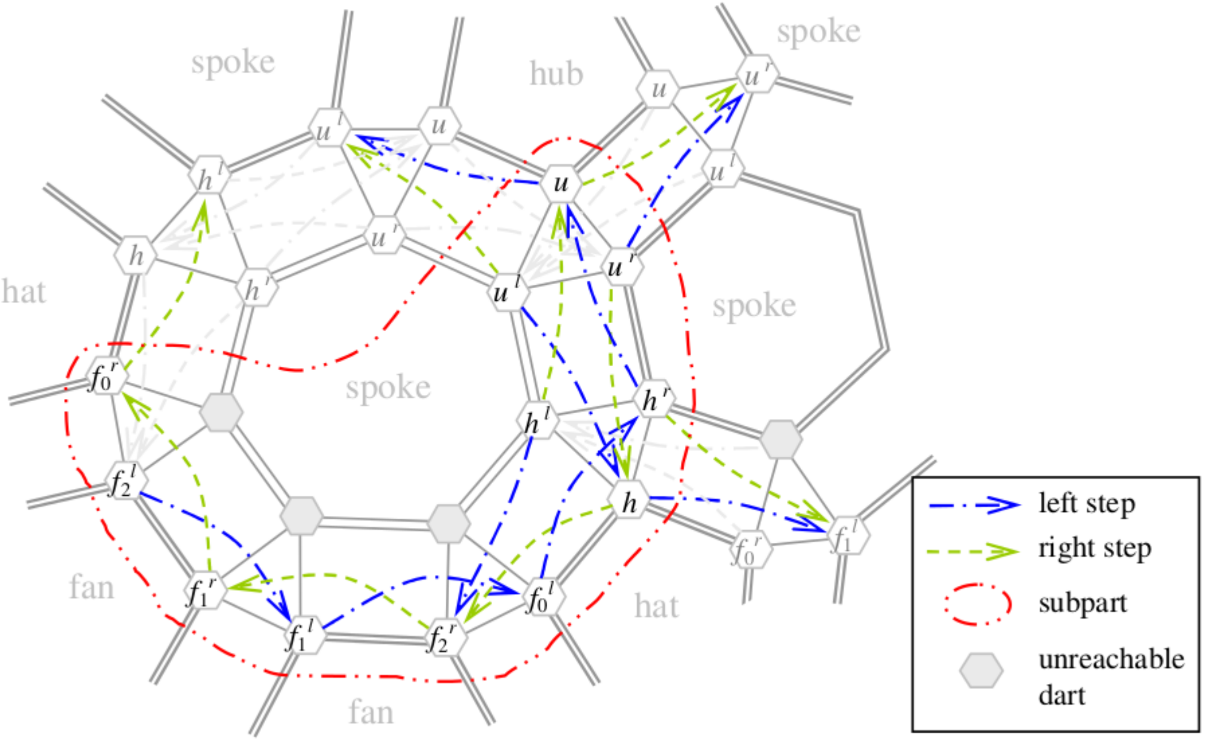
[Cou07] Patrick Cousot. Proving the Absence of Run-Time Errors in Safety-Critical Avionics Code. In Christoph M. Kirsch and Reinhard Wilhelm, editors, *Proceedings of the 7th ACM & IEEE International conference on Embedded software, EMSOFT 2007, Salzburg, Austria*, pages 7–9, 2007.

[DS07] David Delmas and Jean Souyris. Astrée: From Research to Industry. In Hanne Riis Nielson and Gilberto Filé, editors, *Static Analysis, 14th International Symposium, SAS 2007, Kongens Lyngby, Denmark*, volume 4634 of *Lecture Notes in Computer Science*, pages 437–451. Springer, 2007.

[Mau04] Laurent Mauborgne. Astrée: Verification of Absence of Run-Time Error. In René Jacquart, editor, *Building the Information Society, IFIP 18th World Computer Congress, Topical Sessions, Toulouse, France*, pages 385–392. Kluwer Academic Publishers, 2004.

[SD07] Jean Souyris and David Delmas. Experimental Assessment of Astrée on Safety-Critical Avionics Software. In Francesca Saglietti and Norbert Oster, editors, *Computer Safety, Reliability, and Security, 26th International Conference, SAFECOMP 2007, Nuremberg, Germany*, volume 4680 of *Lecture Notes in Computer Science*, pages 479–490. Springer, 2007.

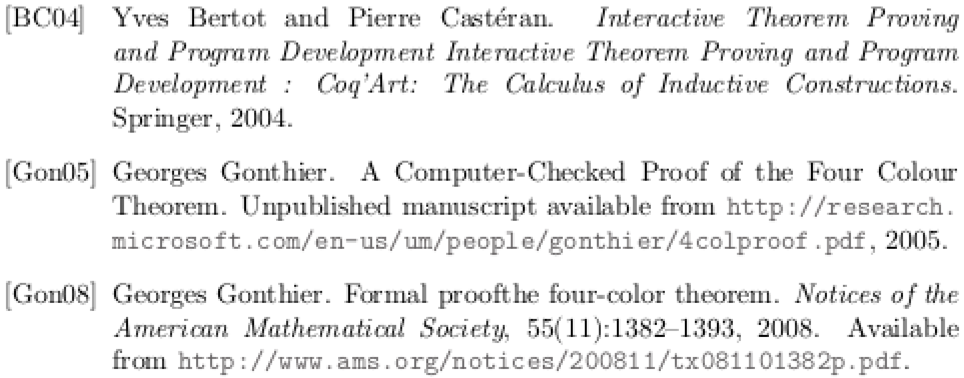
2005



[Gonthier]

Computer-checked proof using Coq of the "four color theorem", the second most famous unsolved problem in mathematics

[2005]



[BC04] Yves Bertot and Pierre Castéran. *Interactive Theorem Proving and Program Development Interactive Theorem Proving and Program Development : Coq'Art: The Calculus of Inductive Constructions.* Springer, 2004.

[Gon05] Georges Gonthier. A Computer-Checked Proof of the Four Colour Theorem. Unpublished manuscript available from `http://research.microsoft.com/en-us/um/people/gonthier/4colproof.pdf`, 2005.

[Gon08] Georges Gonthier. Formal proofthe four-color theorem. *Notices of the American Mathematical Society*, 55(11):1382–1393, 2008. Available from `http://www.ams.org/notices/200811/tx081101382p.pdf`.

2006

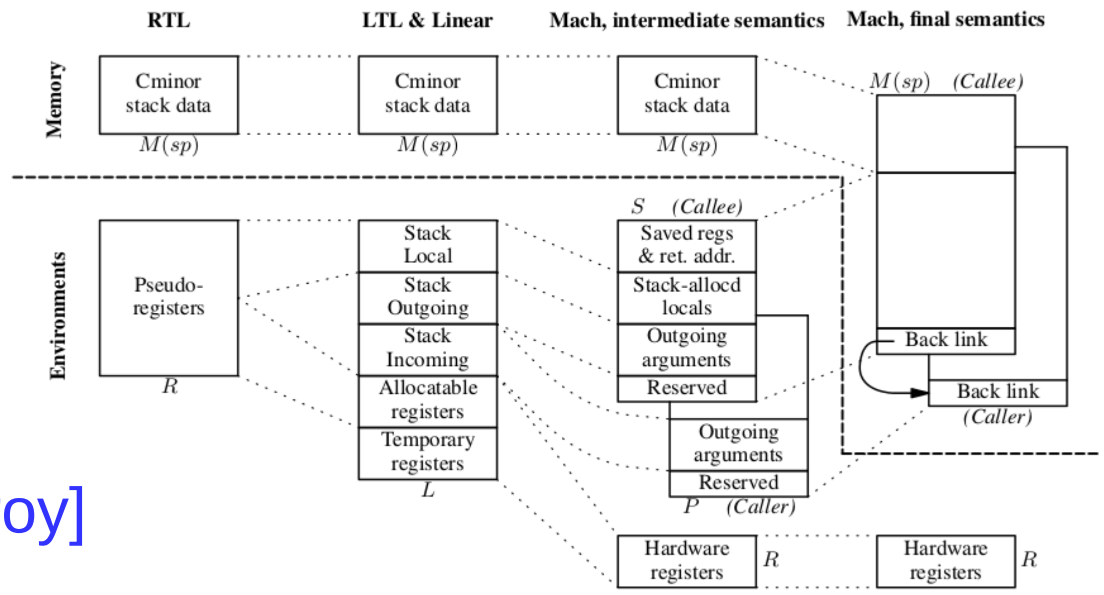
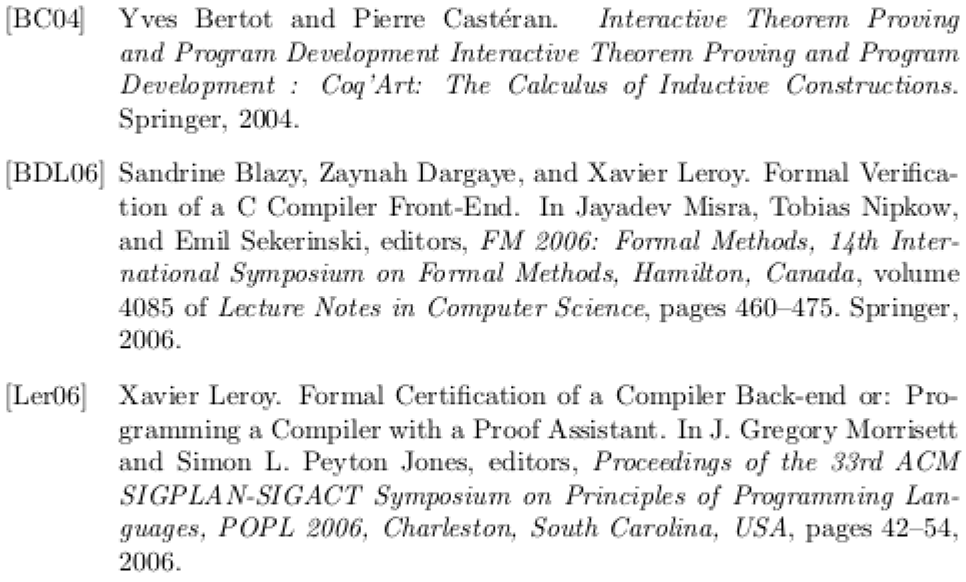


Figure 1. Overview of register allocation and introduction of activation records. For each intermediate language, the placement of function-local data is outlined, either in the memory-allocated activation record (top part) or in non memory-resident execution environments (bottom part).

[Blazy-Dargaye-Leroy]

Formal verification using Coq of a C compiler (front-end and back-end) with a realistic subset of the C language usable for critical embedded software

[2006]



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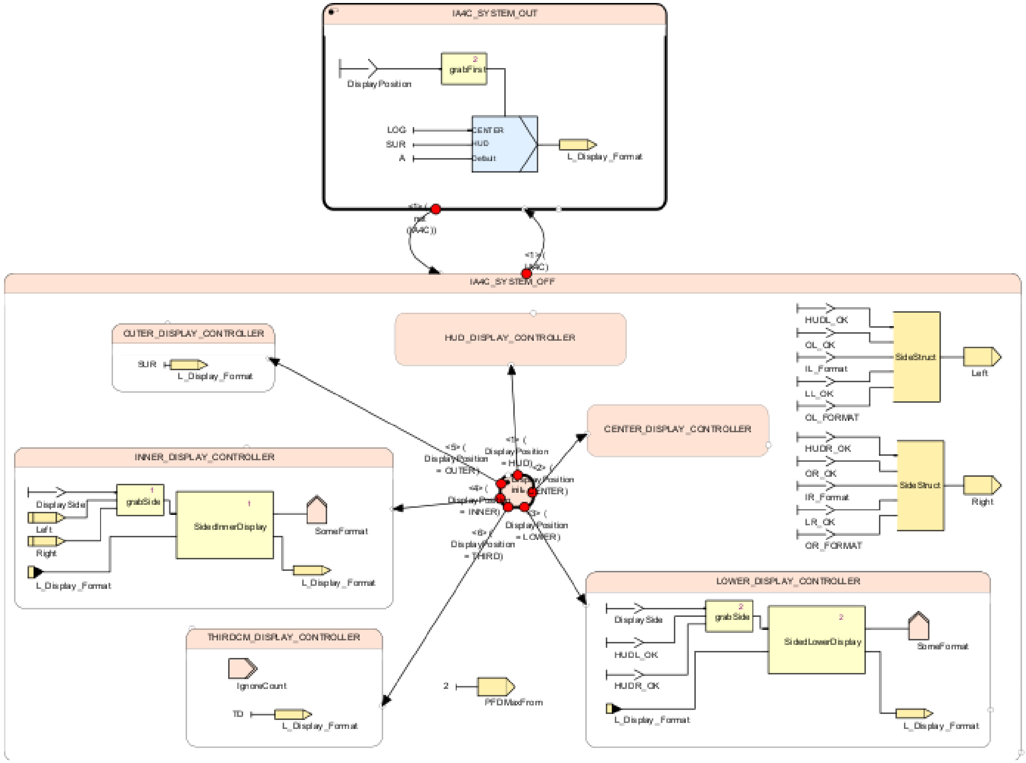
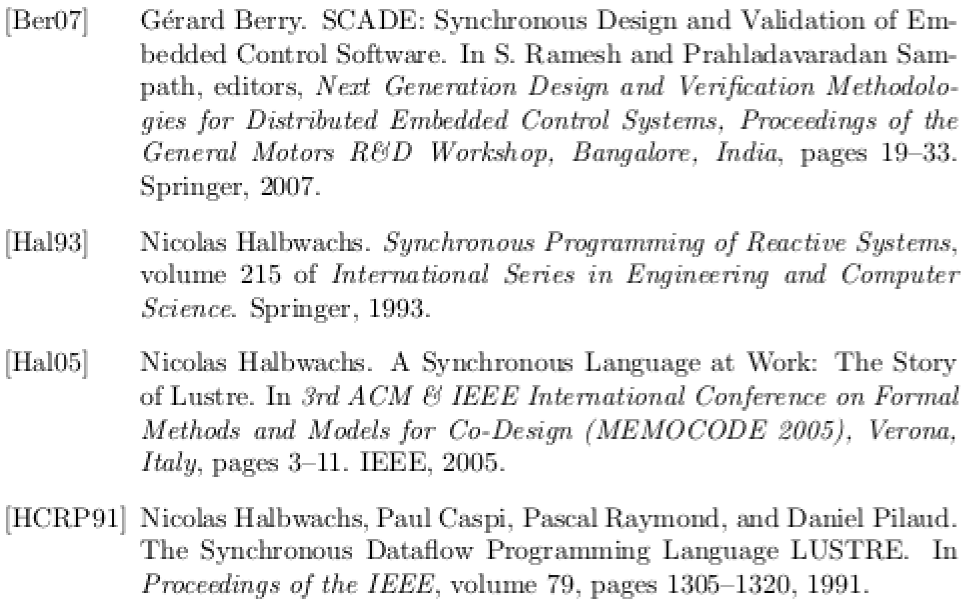
2007



[Berry]
[Halbwachs-Caspi-Raymond-Pilaud]

Design, validation, and implementation of avionics, automotive, railway, and other safety-critical applications using the SCADE tools for the synchronous language Lustre

[2007]



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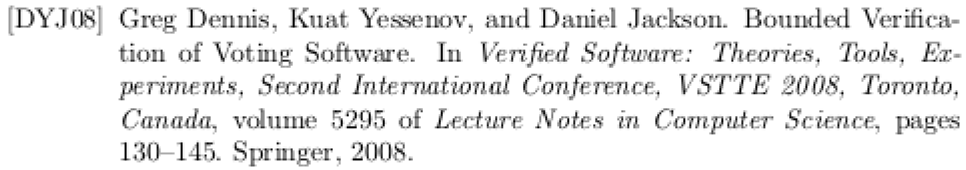
2008

[Dennis-Yessenov-Jackson]

Formal verification using JML and ESC/Java in the vote-tallying part of the KOA open source software used for remote voting in Dutch public elections: discovery of specification errors and programming bugs undetected so far

[2008]



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2009

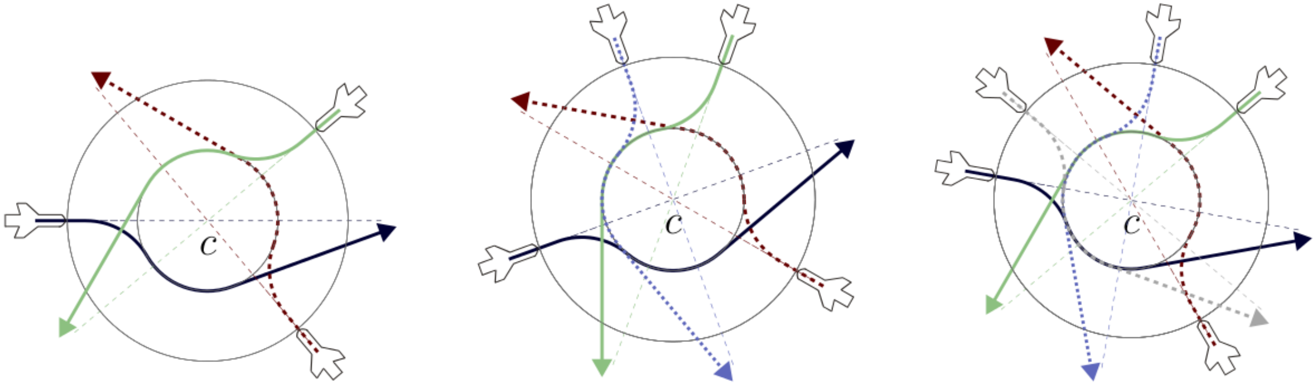
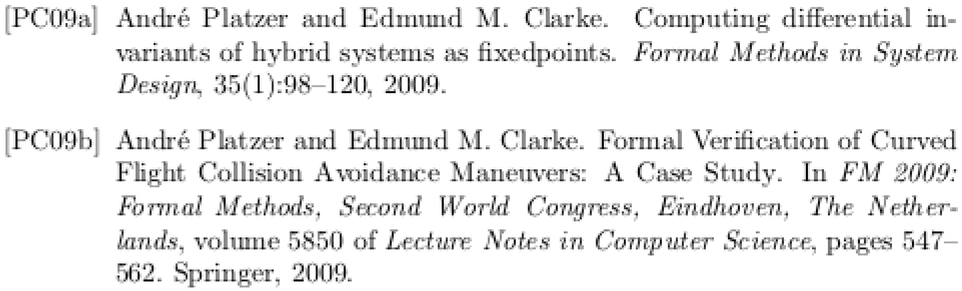


Figure 8: Flyable aircraft roundabout (multiple aircraft)

[Platzer-Clarke]

Formal verification of curved flight collision avoidance maneuvers using the KeYmaera verification tool for hybrid systems

[2009]



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2010

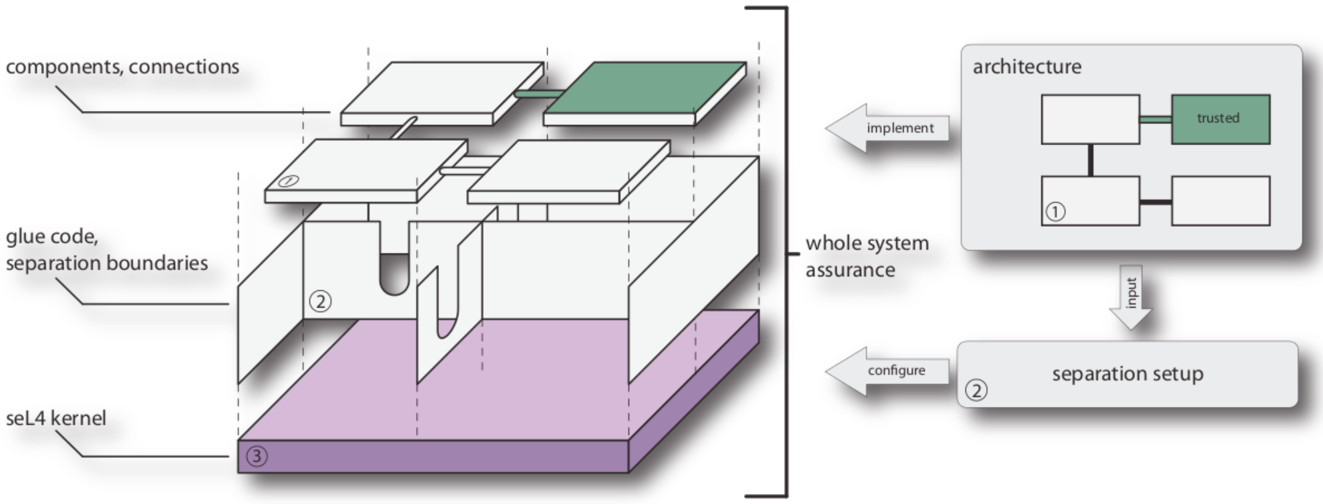
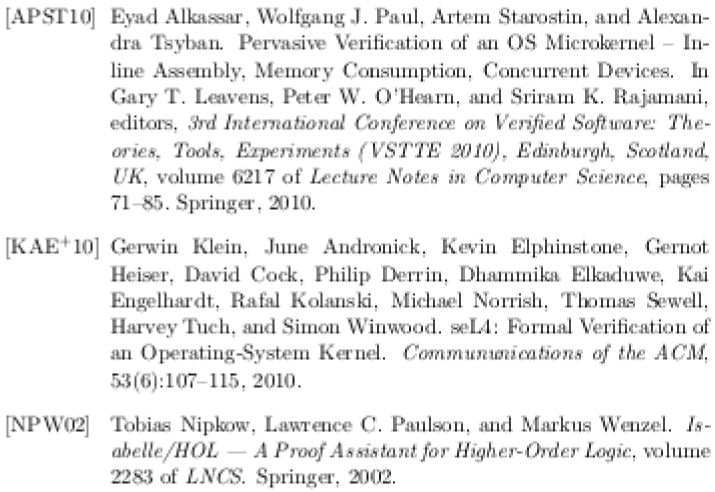


Figure 3: seL4-based system with multiple independent levels of assurance

[Klein-Andronick-Elphinstone-Heiser-Cock-Derrin-Elkaduwe-Engelhardt-Kolanski-Norrish-Sewell-Tuch-Winwood]

Formal verification of the seL4 general purpose operating-system micro-kernel using the Isabelle/HOL theorer prover

[2010]



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2011

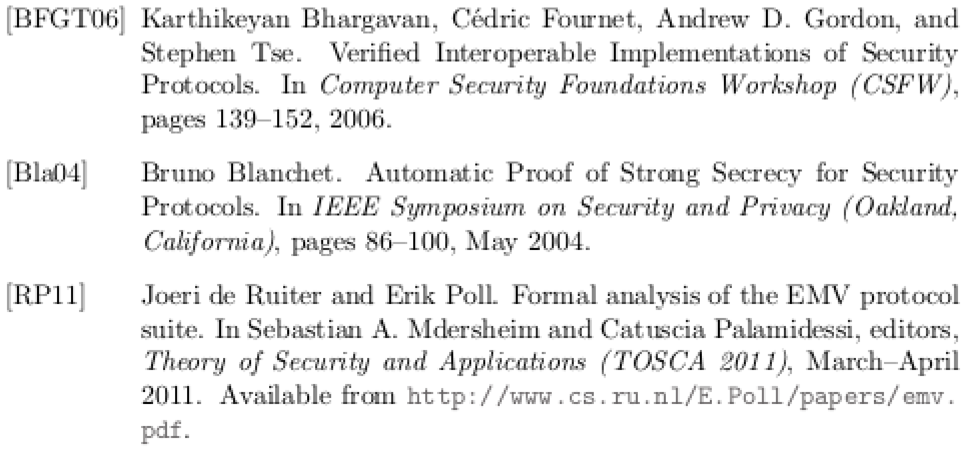
[de Ruiter-Poll]

Formal modelling of the EMV (Europay-MasterCard-Visa) protocol suite in the F# language

Automated analysis of these protocols by joint use of:

- FS2PV translator [Barghavan-Fournet-Gordon-Tse]
- ProVerif [Blanchet]

[2011]



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Conclusion

Conclusion

- About formal methods:
  - Much has been done in 30 years
  - Great diversity of applications
  - Key issue: how to incorporate formal methods in standard engineering practice?
- About this study:
  - A careful selection of success stories
  - Not limitative: there are more success stories
  - Perhaps biased towards over-published works
  - Other lists could be made:
    - 30 most useful fundamental results
    - 30 best software tools