Three decades of success stories in formal methods

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CNRS / Verimag

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)

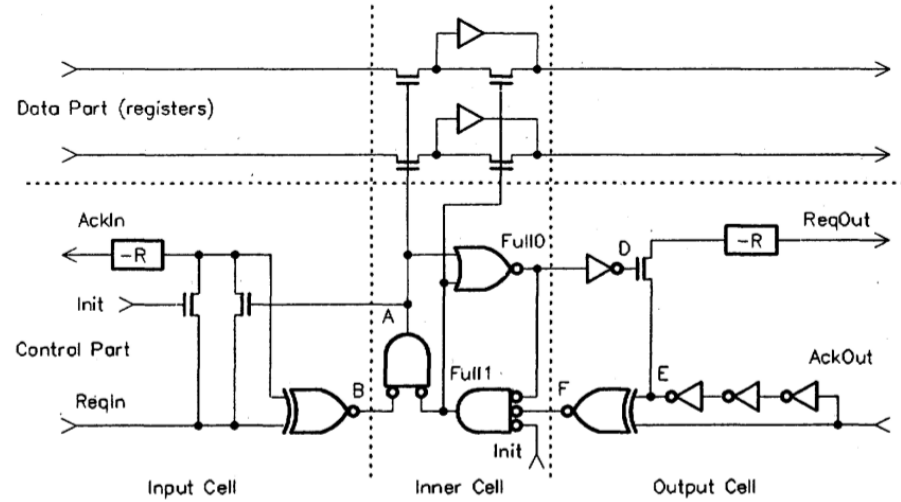
- Exhaustivity is impossible:
  - Only 30 slots for a large formal methods community
  - Google Scholar: 220,000 answers for "formal methods"
  - Nearly 4000 scientists in verification [Woodcock et al]
    - USA : 1000 scientists in verification [Shankar 2009]
    - Europe : 1000
    - Nordic countries : 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]

[BCD86] Michael C. Browne, Edmund M. Clarke, and David L. Dill. Automatic Circuit Verification Using Temporal Logic: Two New Examples. In G. Milne, editor, *Formal Aspects of VLSI Design*. Elsevier Science Publishers (North Holland), 1986.

[BCDM86] Michael C. Browne, Edmund M. Clarke, David L. Dill, and Bud Mishra. Automatic Verification of Sequential Circuits Using Temporal Logic. *IEEE Transactions on Computers*, 35(12):1035–1044, 1986.

[Boc82] Gregor von Bochmann. Hardware Specification with Temporal Logic: An Example. *IEEE Transactions on Computers*, 31(3):223–231, 1982.

[CES83] Edmund M. Clarke, E. Allen Emerson, and A. Prasad Sistla. Automatic Verification of Finite State Concurrent Systems Using Temporal Logic Specifications: A Practical Approach. In *10th Annual ACM Symposium on Principles of Programming Languages (POPL'83)*, pages 117–126, 1983.

[CES86] Edmund M. Clarke, E. Allen Emerson, and A. Prasad Sistla. Automatic Verification of Finite-State Concurrent Systems Using Temporal Logic Specifications. *ACM Transactions on Programming Languages and Systems*, 8(2):244–263, 1986.

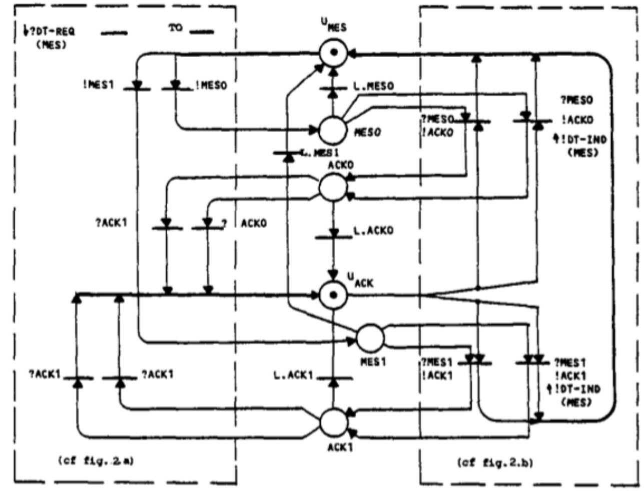
[CM84] Edmund M. Clarke and Bud Mishra. Automatic Verification of Asynchronous Circuits. In *1983 Workshop on Logics of Programs, Carnegie Mellon University, Pittsburgh*, volume 164 of *Lecture Notes in Computer Science*, pages 101–115. Springer, 1984.

[FTM83] Masahiro Fujita, Hidehiko Tanaka, and Tohru Moto-Oka. Temporal Logic Based Hardware Description and its Verification with Prolog. *New Generation Computing*, 1(2):195–203, 1983.

[MC85] Bhubaneswaru Mishra and Edmund M. Clarke. Hierarchical Verification of Asynchronous Circuits Using Temporal Logic. *Theoretical Computer Science*, 38:269–291, 1985.

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]

[Bil83] Jonathan Billington. Abstract Specification of the ISO Transport Service Definition using Labelled Numerical Petri Nets. In Harry Rudin and Colin H. West, editors, *3rd International Workshop on Protocol Specification, Testing and Verification (PSTV'83), Rüschlikon, Switzerland*, pages 173–185. North-Holland, 1983.

[BWB84a] Mirion Y. Bearman, Michael C. Wilbur-Ham, and Jonathan Billington. Some Results of Verifying the OSI Class 0 Transport Protocol. In J. M. Bennet and T. Pearcey, editors, *7th International Conference on Computer Communication (ICCC'84), Sydney, Australia*, pages 597–602, November 1984.

[BWB84b] Mirion Y. Bearman, Michael C. Wilbur-Ham, and Jonathan Billington. Specification and Analysis of the OSI Class 0 Transport Protocol. In J. M. Bennet and T. Pearcey, editors, *7th International Conference on Computer Communication (ICCC'84), Sydney, Australia*, pages 602–607, November 1984.

[BWB85] Mirion Y. Bearman, Michael C. Wilbur-Ham, and Jonathan Billington. Analysis of Open Systems Interconnection Transport Protocol Standard. *Electronics Letters*, 21(15):659–661, 1985.

[BWWH88] Jonathan Billington, Geoffrey R. Wheeler, and Michael C. Wilbur-Ham. PROTEAN: A High-Level Petri Net Tool for the Specification and Verification of Communication Protocols. *IEEE Transactions on Software Engineering*, 14(3):301–316, 1988.

[CAA84] Jean-Pierre Courtiat, Jean-Michel Ayache, and Bernard Algayres. Petri Nets are Good for Protocols. *ACM SIGCOMM Computer Communication Review*, 14(2):66–74, 1984.

[1983]

[JV84] Wolfgang Jürgensen and Son T. Vuong. Formal Specification and Validation of ISO Transport Protocol Components, using Petri Nets. *ACM SIGCOMM Computer Communication Review*, 14(2):75–82, 1984.

[MGL+83] B. Montel, D. Grissault, E. Le Mer, C. Robert, A. Sivet, J.M. Ayache, P. Azema, S. Bachmann, B. Berthomieu, B. Chezalviel-Pradin, J.P. Courtiat, M. Diaz, and J. Dufau. OVIDE: A Software Package for Verifying and Validating Petri Nets. In *Softfair Conference and Development Tools Techniques and Alternatives, Arlington, Virginia, USA*, pages 86–92, 1983.

[WWBG85] Geoffrey R. Wheeler, Michael C. Wilbur-Ham, Jonathan Billington, and J. A. Gilmour. Protocol Analysis using Numerical Petri Nets. In Grzegorz Rozenberg, editor, *6th European Workshop on Applications and Theory in Petri Nets (Advances in Petri Nets'85), Espoo, Finland*, volume 222 of *Lecture Notes in Computer Science*, pages 435–452. Springer, 1985.

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]

[BKM95] Robert S. Boyer, Matt Kaufmann, and J. Strother Moore. The Boyer-Moore Theorem Prover and Its Interactive Enhancement. *Computers and Mathematics with Applications*, 29(2):27–62, 1995.

[BM84a] Robert S. Boyer and J. Strother Moore. A Mechanical Proof of the Unsolvability of the Halting Problem. *Journal of the ACM*, 31(3):441–458, 1984.

[BM84b] Robert S. Boyer and J. Strother Moore. Proof Checking the RSA Public Key Encryption Algorithm. *American Mathematical Monthly*, 91(3):181–189, 1984.

[BM84c] Robert S. Boyer and J. Strother Moore. Proof-Checking, Theorem-Proving, and Program Verification. In W. W. Bledsoe and D. W. Loveland, editors, *Automated Theorem Proving: After 25 Years, Providence, Rhode Island, USA*, volume 29 of *Contemporary Mathematics*, pages 119–132. American Mathematical Society, 1984.

[Sha85] Natarajan Shankar. Towards Mechanical Metamathematics. *Journal of Automated Reasoning*, 1(4):407–434, 1985.

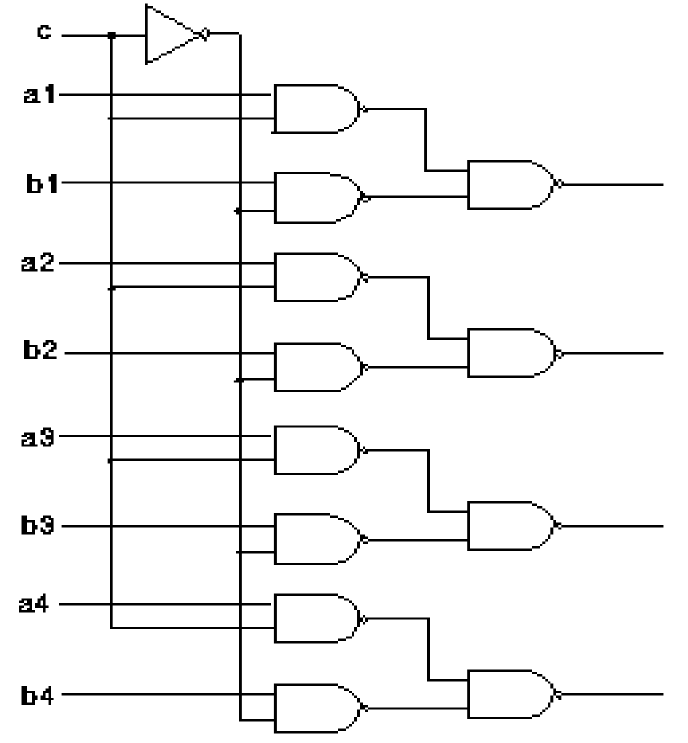
[Sha86] Natarajan Shankar. *Proof Checking Metamathematics*. PhD thesis, The University of Texas at Austin, 1986.

[Sha88] Natarajan Shankar. A mechanical proof of the Church-Rosser theorem. *Journal of the ACM*, 35(3):475–522, 1988.

[Sha94] Natarajan Shankar. *Metamathematics, Machines and Gödel's Proof*, volume 38 of *Cambridge Tracts in Theoretical Computer Science*. Cambridge University Press, 1994.

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]

[Hun85] Warren A. Hunt. *FM8501: A Verified Microprocessor*. PhD thesis, The University of Texas at Austin, 1985. Available as the book "FM8501: A Verified Microprocessor", volume 795 of Lecture Notes in Computer Science, Springer-Verlag, 1994.

[Hun89] Warren A. Hunt. Microprocessor Design Verification. *Journal of Automated Reasoning*, 5(4):429–460, 1989.

[Hun94] Warren A. Hunt. *FM8501: A Verified Microprocessor*, volume 795 of *Lecture Notes in Computer Science*. Springer-Verlag, 1994.

1986

[West] + [Rudin, Zafiropulo]

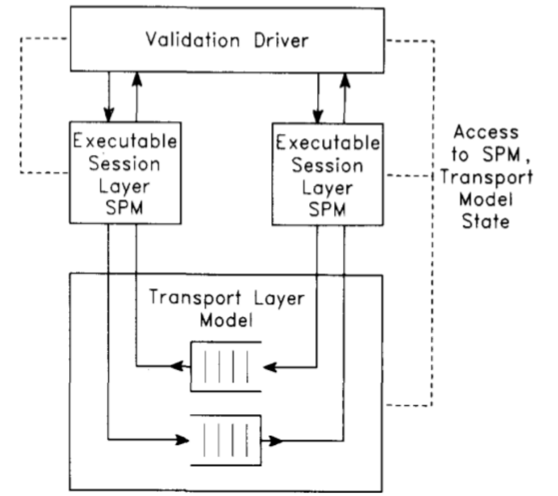


Fig. 2. The OSI session layer validation system.

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]

[Rud86] Harry Rudin. Tools for Protocols Driven by Formal Specifications. In Albert T. Kündig, Richard E. Bührer, and Jacques Dähler, editors, *Embedded Systems: New Approaches to Their Formal Description and Design, An Advances Course, Zürich, Switzerland*, volume 284 of *Lecture Notes in Computer Science*, pages 127–152. Springer, 1986.

[RWZ78] Harry Rudin, Colin H. West, and Pitro Zafiropulo. Automated Protocol Validation: One Chain of Development. *Computer Networks*, 2:373–380, 1978.

[Saj84] Michal Sajkowski. Protocol Verification Techniques: Status Quo and Perspectives. In Yechiam Yemini, Robert E. Strom, and Shaula Yemini, editors, *4th International Workshop on Protocol Specification, Testing and Verification (PSTV'84), Skytop Lodge, Pennsylvania, USA*, pages 697–720. North-Holland, 1984.

[Sun78] Carl A. Sunshine. Survey of Protocol Definition and Verification Techniques. *Computer Networks*, 2(4–5):346–350, 1978.

[Wes78] Colin H. West. General Technique for Communications Protocol Validation. *IBM Journal of Research and Development*, 22(4):393–404, July 1978.

[Wes86] Colin H. West. A Validation of the OSI Session Layer Protocol. *Computer Networks*, 11(3):173–182, March 1986.

[ZWR+82] Pitro Zafiropulo, Colin H. West, Harry Rudin, D. D. Cowan, and Daniel Brand. Protocol Analysis and Synthesis Using a State Transition Model. In P. E. Green Jr., editor, *Computer Networks Architectures and Protocols*, pages 645–669. Plenum Publishing Company, New York, 1982.

1987

[Graf-Richier-Rodriguez-Sifakis-Voiron]

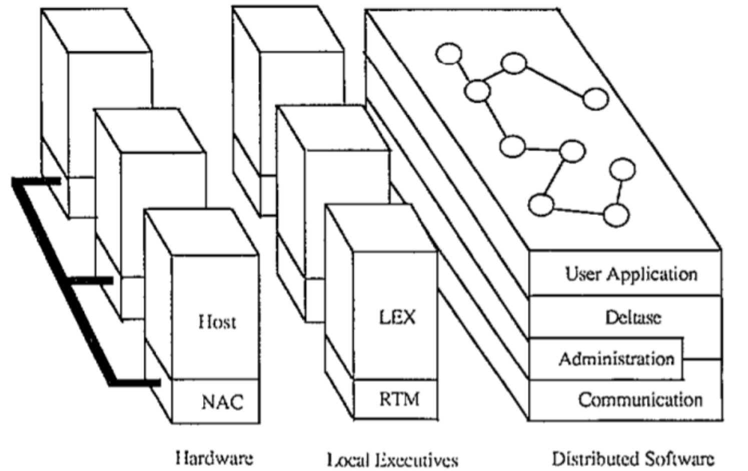


Figure 1. Abstract view of the Delta-4 architecture.

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.

[GRRV90] Susanne Graf, Jean-Luc Richier, Carlos Rodriguez, and Jacques Voiron. What are the Limits of Model Checking Methods for the Verification of Real Life Protocols? In *International Workshop on Automatic Verification Methods for Finite State Systems, Grenoble, France, June 1989*, volume 407 of *Lecture Notes in Computer Science*, pages 275–285. Springer, 1990.

[Hol92] Gerard J. Holzmann. Protocol Design: Redefining the State of the Art. *IEEE Software*, 9(1):17–22, 1992. Full version available from `http://spinroot.com/gerard/pdf/ieee91.pdf`.

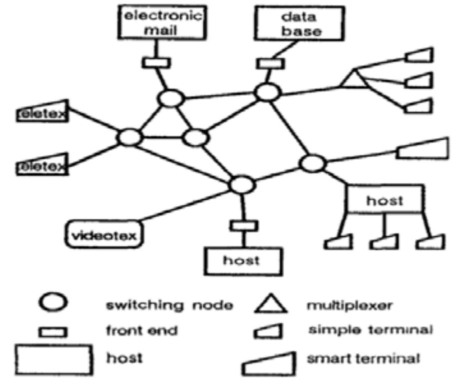
[ISO89] ISO (International Organization for Standardization). Information Processing Systems – Open Systems Interconnection – Estelle: A Formal Description Technique Based on an Extended State Transition Model. International Standard 9074:1989, ISO/IEC, Geneva, 1989. Standard withdrawn in 1999.

[RRSV87a] Jean-Luc Richier, Carlos Rodriguez, Joseph Sifakis, and Jacques Voiron. Verification in XESAR of the Sliding Window Protocol. In *Proceedings of the IFIP WG6.1 7th Int. Conference on Protocol Specification, Testing and Verification, Zurich*. North-Holland, 1987.

[RRSV87b] Jean-Luc Richier, Carlos Rodrìguez, Joseph Sifakis, and Jacques Voiron. Xesar: A Tool for Protocol Validation – User's Guide. LGI-Imag, Grenoble, France, 1987.

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]

[BK84] Ed Brinksma and Günter Karjoth. A Specification of the OSI Transport Service in LOTOS. In Yechiam Yemini, Robert E. Strom, and Shaula Yemini, editors, *4th International Workshop on Protocol Specification, Testing and Verification (PSTV'84), Skytop Lodge, Pennsylvania, USA*, pages 227–251. North-Holland, 1984.

[Boc89] Gregor von Bochmann. Protocol Specification for OSI. *Computer Networks and ISDN Systems*, 18(3):167–184, 1989.

[FA88] David Freestone and Sukhvinder S. Aujla. Specifying ROSE in LOTOS. In Kenneth J. Turner, editor, *1st International Conference on Formal Description Techniques (FORTE'88), Stirling, Scotland, United Kingdom*, pages 231–245. North-Holland, 1988.

[Fer89] Luís Ferreira Pires. On the Use of LOTOS to Support the Design of a Connection-oriented Internetting Protocol. In *ESPRIT'89 Conference, Dordrecht, the Netherlands*, pages 957–970. North-Holland, 1989.

[ISO89a] ISO (International Organization for Standardization). Information Processing Systems – Open Systems Interconnection – LOTOS – A Formal Description Technique Based on the Temporal Ordering of Observational Behaviour. International Standard 8807:1989, ISO/IEC, Geneva, 1989.

[ISO89b] ISO (International Organization for Standardization). Information Processing Systems – Open Systems Interconnection – LOTOS Description of the Session Protocol. Technical Recommendation TR 9572:1989, ISO/IEC, Geneva, 1989. Withdrawn on 1997-03-07.

[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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[ISO92a] ISO (International Organization for Standardization). Information Technology – Telecommunications and Information Exchange between Systems – Formal Description of ISO 8072 in LOTOS. Technical Recommendation TR 10023:1992, ISO/IEC, Geneva, 1992. (LOTOS description of the connection-oriented transport service) – Withdrawn on 2004-04-23.

[ISO92b] ISO (International Organization for Standardization). Information Technology – Telecommunications and Information Exchange between Systems – Formal description of ISO 8073 (Classes 0, 1, 2, 3) in LOTOS. Technical Recommendation TR 10024:1992, ISO/IEC, Geneva, 1992. (LOTOS description of the connection-oriented transport protocol) – Withdrawn on 2004-04-23).

[ISO95a] ISO (International Organization for Standardization). Information Technology – Open Systems Interconnection – LOTOS Description of the CCR Protocol. Technical Recommendation TR 11590:1995, ISO/IEC, Geneva, 1995. Withdrawn on 2008-05-08.

[ISO95b] ISO (International Organization for Standardization). Information Technology – Open Systems Interconnection – LOTOS Description of the CCR Service. Technical Recommendation TR 11589:1995, ISO/IEC, Geneva, 1995. Withdrawn on 2008-05-08.

[LS88] Jeroen van de Lagemaat and Giuseppe Scollo. On the Use of LOTOS for the Formal Description of a Transport Protocol. In Kenneth J. Turner, editor, *1st International Conference on Formal Description Techniques (FORTE'88), Stirling, Scotland, United Kingdom*, pages 247–261. North-Holland, 1988.

[Peh89] Björn Pehrson. Protocol Verification for OSI. *Computer Networks and ISDN Systems*, 18(3):185–201, 1989.

[SAC88] Marten van Sinderen, Ibrahim Ajubi, and Fausto Caneschi. The Application of LOTOS for the Formal Description of the ISO Session Layer. In Kenneth J. Turner, editor, *1st International Conference on Formal Description Techniques (FORTE'88), Stirling, Scotland, United Kingdom*, pages 263–277. North-Holland, 1988.

[SW90] Marten van Sinderen and Ing Widya. On the Design and Formal Specification of a Transaction Processing Protocol. In Juan Quemada, José A. Mañas, and Enrique Vázquez, editors, *3rd International Conference on Formal Description Techniques for*

[1988]

Distributed Systems and Communication Protocols (FORTE'90), Madrid, Spain, pages 411–426. North-Holland, 1990.

[Tur89] Kenneth J. Turner. A LOTOS Case Study: Specification of the OSI Connection-Oriented Network Service. Presented at the OTC (Overseas Telecommunications Commission) Workshop on Formal Description Techniques, Sydney, Australia, July 1989.

[VS87] Chris A. Vissers and Giuseppe Scollo. Formal Specification in OSI. In Günter Müller and Robert Blanc, editors, *International Seminar on Networking in Open Systems*, volume 248 of *Lecture Notes in Computer Science*, pages 338–359. Springer, 1987.

[WH93] Ing Widya and Gert-Jan van der Heijden. Towards an Implementation-oriented Specification of TP Protocol in LOTOS. In Jim Woodcock and Peter Gorm Larsen, editors, *1st International Symposium of Formal Methods Europe on Industrial-Strength Formal Methods (FME'93), Odense, Denmark*, volume 670 of *Lecture Notes in Computer Science*, pages 93–109. Springer, 1993.

1989

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

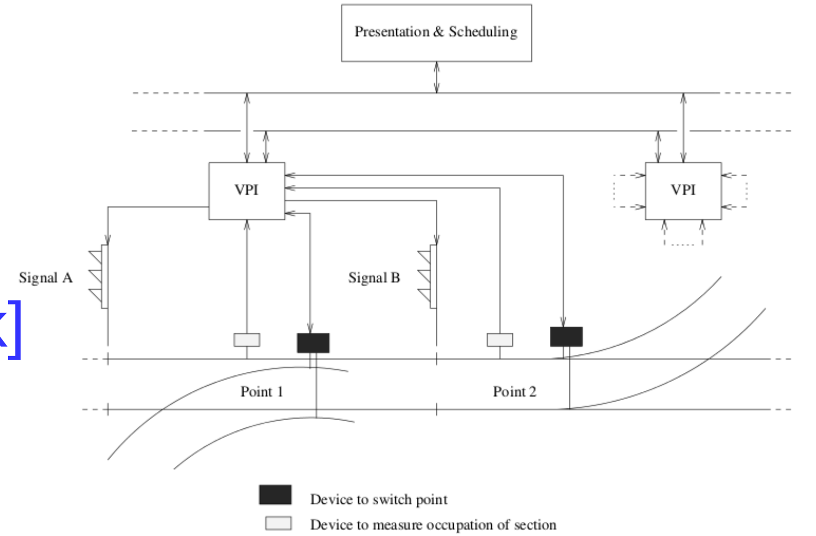

Figure 1: VPIs and their environment

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]

[Bor97] Arne Borälv. The Industrial Success of Verification Tools Based on Stålmarck's Method. In Orna Grumberg, editor, *9th International Conference on Computer Aided Verification (CAV'97), Haifa, Israel*, volume 1254 of *Lecture Notes in Computer Science*, pages 7–10. Springer, 1997.

[Bor98] Arne Borälv. Case Study: Formal Verification of a Computerized Railway Interlocking. *Formal Aspects of Computing*, 10(4):338–360, 1998.

[Eis99] Cindy Eisner. Using Symbolic Model Checking to Verify the Railway Stations of Hoorn-Kersenboogerd and Heerhugowaard. In Laurence Pierre and Thomas Kropf, editors, *10th IFIP Conference on Correct Hardware Design and Verification Methods (CHARME'99), Bad Herrenalb, Germany*, volume 1703 of *Lecture Notes in Computer Science*, pages 97–109. Springer, 1999.

[Fok96] Wan F. Fokkink. Safety Criteria for the Vital Processor Interlocking at Hoorn-Kersenboogerd. In *5th Conference on Computers in Railways (COMPRAIL'96) – Volume I: Railway Systems and Management, Berlin, Germany*, pages 101–110. Computational Mechanics Publications, 1996.

[GKV94] J.F. Groote, J.W.C. Koorn, and S.F.M. van Vlijmen. The Safety Guaranteeing System at Station Hoorn-Kersenboogerd. Technical Report 121, Logic Group Preprint Series, Department of Philosophy, Utrecht University, 1994. Available from `http://www.phil.uu.nl/preprints/lgps`.

[GKV95] J.F. Groote, J.W.C. Koorn, and S.F.M. van Vlijmen. The Safety Guaranteeing System at Station Hoorn-Kersenboogerd (Extended Abstract). In *10th Annual Conference on Computer Assurance (COMPASS95), Gaithersburg, Maryland, USA*, pages 57–68. IEEE Press, 1995.

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[Stå89a] Gunnar Stålmarck. A Note on the Computational Complexity of the Pure Classical Implication Calculus. *Information Processing Letters*, 31(6):277–278, 1989.

[Stå89b] Gunnar Stålmarck. A System for Determining Propositional Logic Theorems by Applying Values and Rules to Triplets that Are Generated from a Formula. Swedish Patent No. 467 076 (approved 1992), U.S. Patent No. 5 276 897 (approved 1994), European Patent No. 0403 454 (approved 1995), 1989.

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]

[ALN+91] Jean-Raymond Abrial, Matthew K. O. Lee, David Neilson, P. N. Scharbach, and Ib Holm Sørensen. The B-Method. In *4th International Symposium of VDM Europe on Formal Software Development (VDM'91), Noordwijkerhout*, volume 552 of *Lecture Notes in Computer Science*, pages 398–405. Springer, 1991.

[CDDM92] Michel Carnot, Clara DaSilva, Babk Dehbonei, and Fernando Meija. Error-free Software Development for Critical Systems using the B-Methodology. In *3rd International IEEE Symposium on Software Reliability Engineering (ISSRE'92), Research Triangle Park, North Carolina, USA*. IEEE Computer Society, 1992.

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[GH90] Gérard D. Guiho and Claude Hennebert. SACEM Software Validation (Experience Report). In *12th International Conference on Software Engineering (ICSE'90), Nice, France*, pages 186–191. IEEE Computer Society, 1990.

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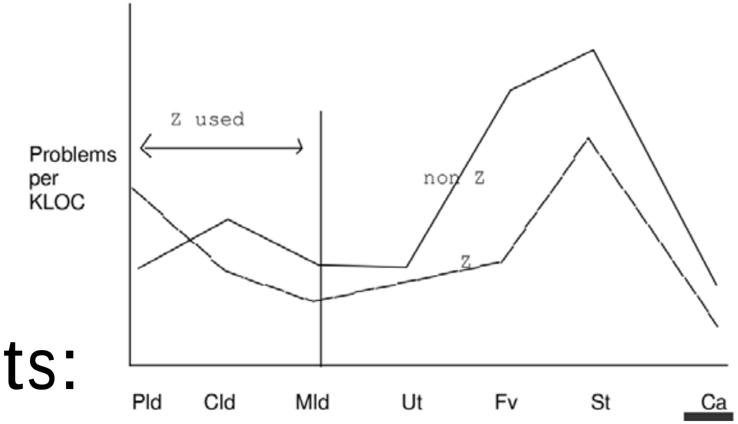
1991

[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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[HK91] Ian Houston and Steve King. CICS Project Report: Experiences and Results from the Use of Z in IBM. In Søren Prehn and W. J. Toetenel, editors, *Formal Software Development — 4th International Symposium of VDM Europe (VDM'91), Noordwijkerhout, The Netherlands, Volume 1: Conference Contributions*, volume 551 of *Lecture Notes in Computer Science*, pages 588–596. Springer, 1991.

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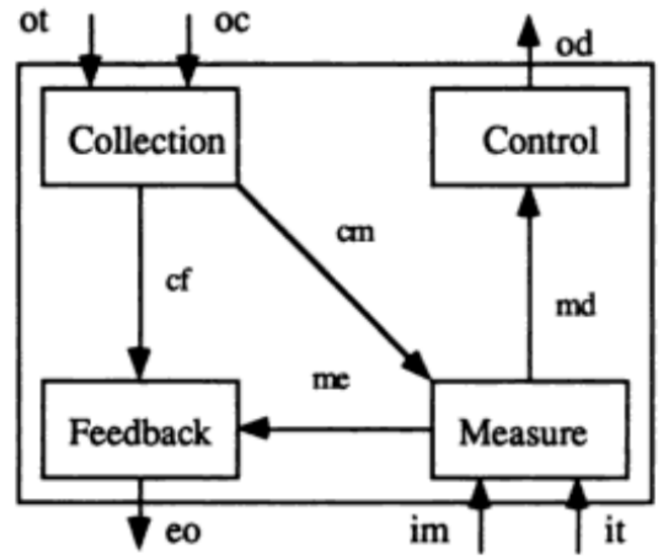
1992

[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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[Pat93] Fabio Paternò. Definition of Properties of User Interfaces Using Action-Based Temporal Logic. In A. Monk, D. Diaper, and M. D. Harrison, editors, *5th International Conference on Software Engineering and Knowledge Engineering (SEKE'93), San Francisco Bay, USA*, pages 314–318. Knowledge Systems Institute, 1993.

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[PM94] Fabio Paternò and Menica Mezzanotte. Analysing Matis by Interactors and ACTL. Technical report SM (System Modelling)/WP36 of the ESPRIT Basic Research Action 7040 "Amodeus". Available from `ftp://ftp.mrc-cbu.cam.ac.uk/amodeus/sysmod/sm_wp36.rtf`, September 1994.

[PSL95] Fabio Paternò, M. S. Sciacchitano, and Jonas Löwgren. A User Interface Evaluation Mapping Physical User Actions to Task-Driven Formal Specifications. In Philippe A. Palanque and Rémi Bastide, editors, *Eurographics Workshop on Design, Specification and Verification of Interactive Systems (DSV-IS'95), Toulouse, France*, pages 35–53. Springer, 1995.

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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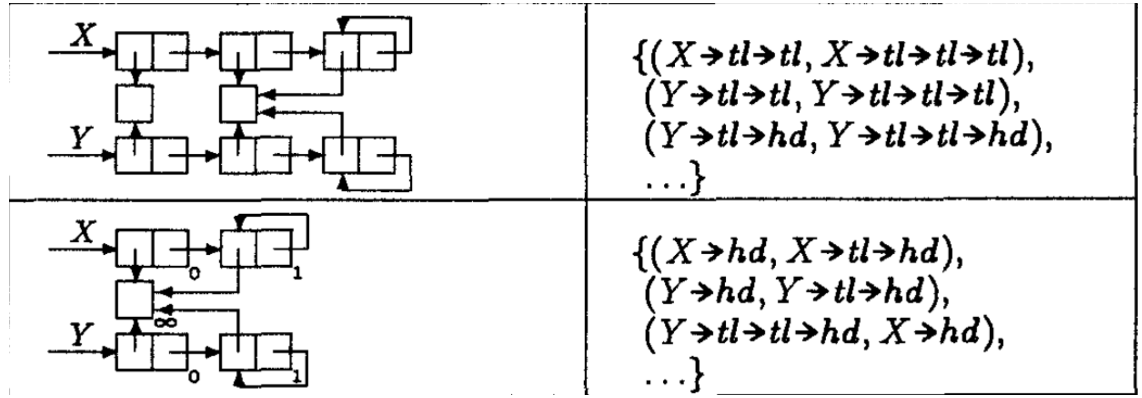
1994

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



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]

[And94] Lars Ole Andersen. *Program Analysis and Specialization for the C Programming Language*. PhD thesis, DIKU – University of Copenhagen, Denmark, 1994. Also available as DIKU report 94/19.

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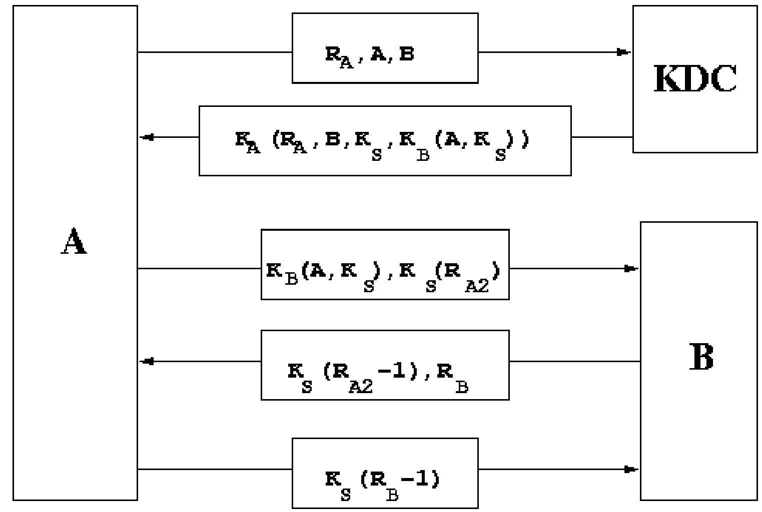
[Eva96] David Evans. Static Detection of Dynamic Memory Errors. In *ACM SIGPLAN Conference on Programming Language Design and Implementation (PLDI'96), Philadephia, Pennsylvania, USA*, volume 31(5) of *SIGPLAN Notices*, pages 44–53. ACM Press, 1996.

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]

[Hoa85] C.A.R. Hoare. *Communicating Sequential Processes*. Prentice Hall, April 1985. New edition available from `http://www.usingcsp.com`.

[Low95] Gavin Lowe. An Attack on the Needham-Schroeder Public-Key Authentication Protocol. *Information Processing Letters*, 56(3):131–133, 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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[TWC01] Jan Tretmans, Klaas Wijbrans, and Michel R. V. Chaudron. Software Engineering with Formal Methods: The Development of a Storm Surge Barrier Control System Revisiting Seven Myths of Formal Methods. *Formal Methods in System Design*, 19(2):195–215, 2001.

1997

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

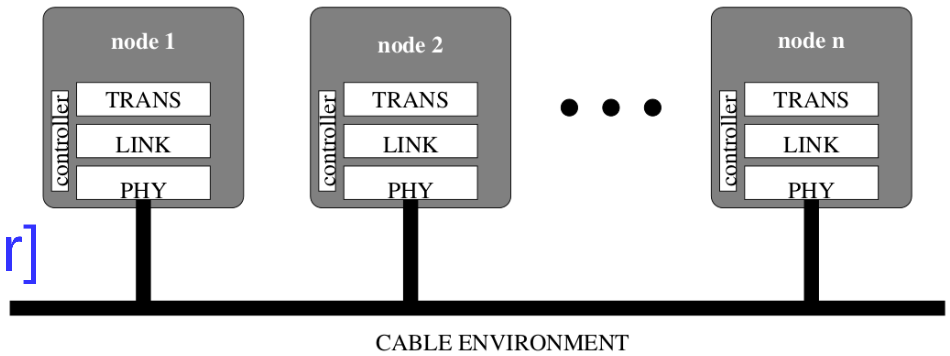

Figure 1: Serial Bus architecture.

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

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

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[KHR97] Lars Khne, Jozef Hooman, and Willem-Paul de Roever. Towards Mechanical Verification of Parts of the IEEE P1394 Serial Bus. In Ignac Lovrek, editor, *Proceedings of the 2nd COST 247 International Workshop on Applied Formal Methods in System Design (Zagreb, Croatia)*, June 1997. Available from `http://www.cs.ru.nl/~hooman/P1394.html`.

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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.

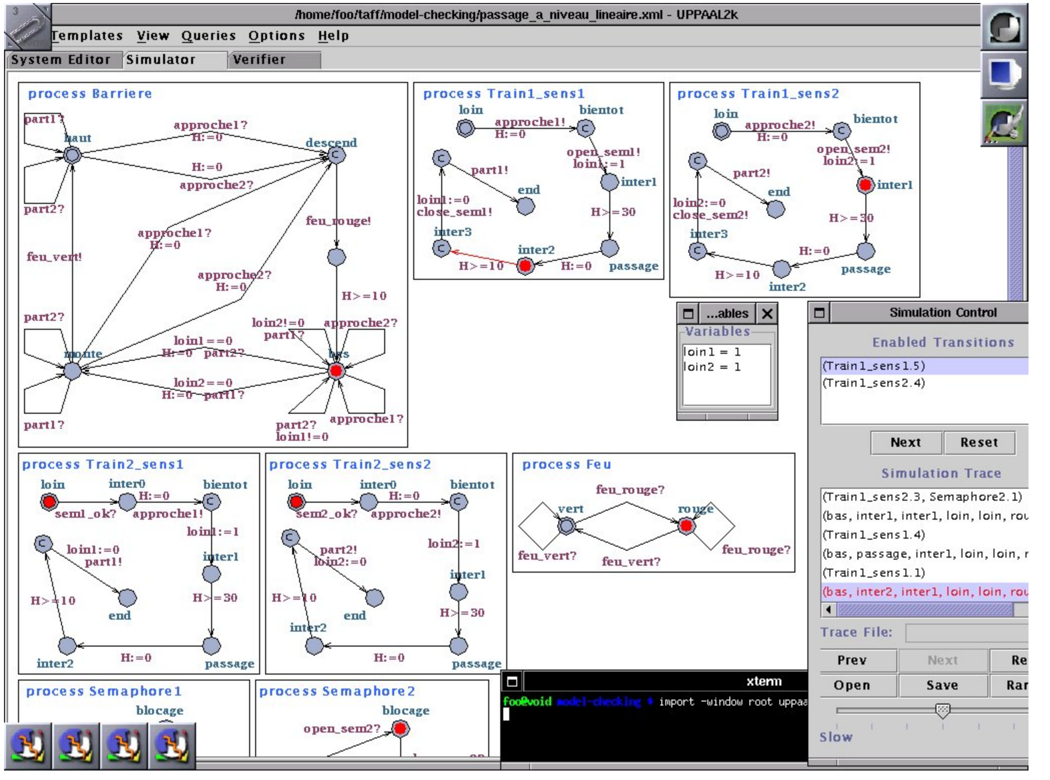
[ORSS96] Sam Owre, John Rushby, Natarjan Shankar, and M. Srivas. PVS: Combining specification, proof checking and model-checking. In *CAV'96*, volume 1102 of *LNCS*, 1996.

[SM97] Mihaela Sighireanu and Radu Mateescu. Validation of the Link Layer Protocol of the IEEE-1394 Serial Bus ("FireWire"): an Experiment with E-LOTOS. In Ignac Lovrek, editor, *Proceedings of the 2nd COST 247 International Workshop on Applied Formal Methods in System Design (Zagreb, Croatia)*, June 1997. Full version available from http://hal.inria.fr/inria-00073516 as INRIA Research Report RR-3172.

[SM98] Mihaela Sighireanu and Radu Mateescu. Verification of the Link Layer Protocol of the IEEE-1394 Serial Bus (FireWire): An Experiment with E-LOTOS. *Springer International Journal on Software Tools for Technology Transfer (STTT)*, 2(1):68–88, July 1998.

1998

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



Automated verication 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.

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[BFM98] Howard Bowman, Giorgio P. Faconti, and Mieke Massink. Specification and Verification of Media Constraints using Uppaal. In Panos Markopoulos and Peter Johnson, editors, *5th International Eurographics Workshop on the Design, Specification and Verification of Interactive Systems, Abingdon, United Kingdom*, volume 1 of *Eurographic series*, pages 261–277. Springer, 1998.

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

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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.

[LPY01] Magnus Lindahl, Paul Pettersson, and Wang Yi. Formal Design and Analysis of a Gear Controller. *STTT*, 3(3):353–368, 2001.

[TY98] Stavros Tripakis and Sergio Yovine. Verification of the Fast Reservation Protocol with Delayed Transmission using the Tool Kronos. In *4th IEEE Real-Time Technology and Applications Symposium (RTAS'98), Denver, Colorado*, pages 165–170. IEEE Computer Society Press, 1998.

[Yov97] Sergio Yovine. Kronos: A verification tool for real-time systems. *International Journal of Software Tools for Technology Transfer (STTT)*, 1(1–2):123–133, 1997.

1999

[Pfeifer-Schwier-vonEnke-Rushby-Sorea-Steiner]

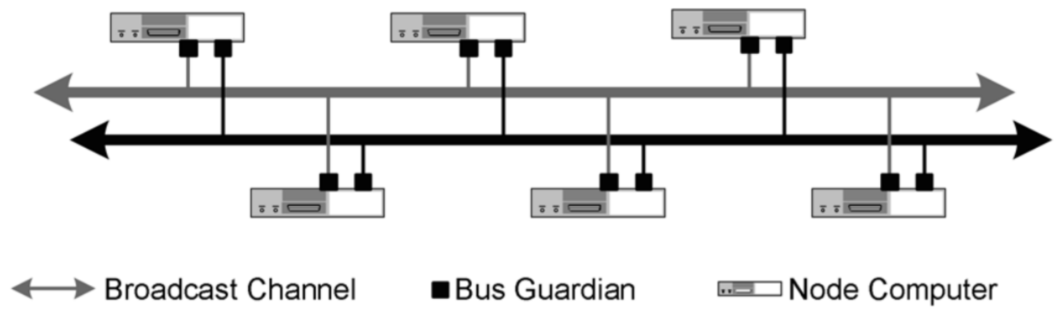

Fig. 5. Topology of TTA-bus

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.

[KB03] Hermann Kopetz and Günther Bauer. The Time-Triggered Architecture. *Proceedings of the IEEE*, 91(1):112–126, 2003.

[KBE+95] Hermann Kopetz, Martin Braun, Christian Ebner, Andreas Krüger, Dietmar Millinger, Roman Nossal, and Anton V. Schedl. The Design of Large Real-Time Systems: The Time-Triggered Approach. In *IEEE Real-Time Systems Symposium*, pages 182–189, 1995.

[KG94] Hermann Kopetz and Günter Grünsteidl. TTP - A Protocol for Fault-Tolerant Real-Time Systems. *IEEE Computer*, 27(1):14–23, 1994.

[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.

[ORSS96] Sam Owre, John Rushby, Natarjan Shankar, and M. Srivas. PVS: Combining specification, proof checking and model-checking. In *CAV'96*, volume 1102 of *LNCS*, 1996.

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[Rus99] John M. Rushby. Systematic Formal Verification for Fault-Tolerant Time-Triggered Algorithms. *IEEE Transactions on Software Engineering*, 25(5):651–660, 1999.

[Rus01] John M. Rushby. Bus architectures for safety-critical embedded systems. In *Embedded Software, First International Workshop, EMSOFT 2001*, volume 2211 of *Lecture Notes in Computer Science*, pages 306–323. Springer, 2001.

[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.

[SRSP04] Wilfried Steiner, John M. Rushby, Maria Sorea, and Holger Pfeifer. Model Checking a Fault-Tolerant Startup Algorithm: From Design Exploration To Exhaustive Fault Simulation. In *International Conference on Dependable Systems and Networks (DSN 2004), Florence, Italy*, pages 189–198. IEEE Computer Society, 2004.

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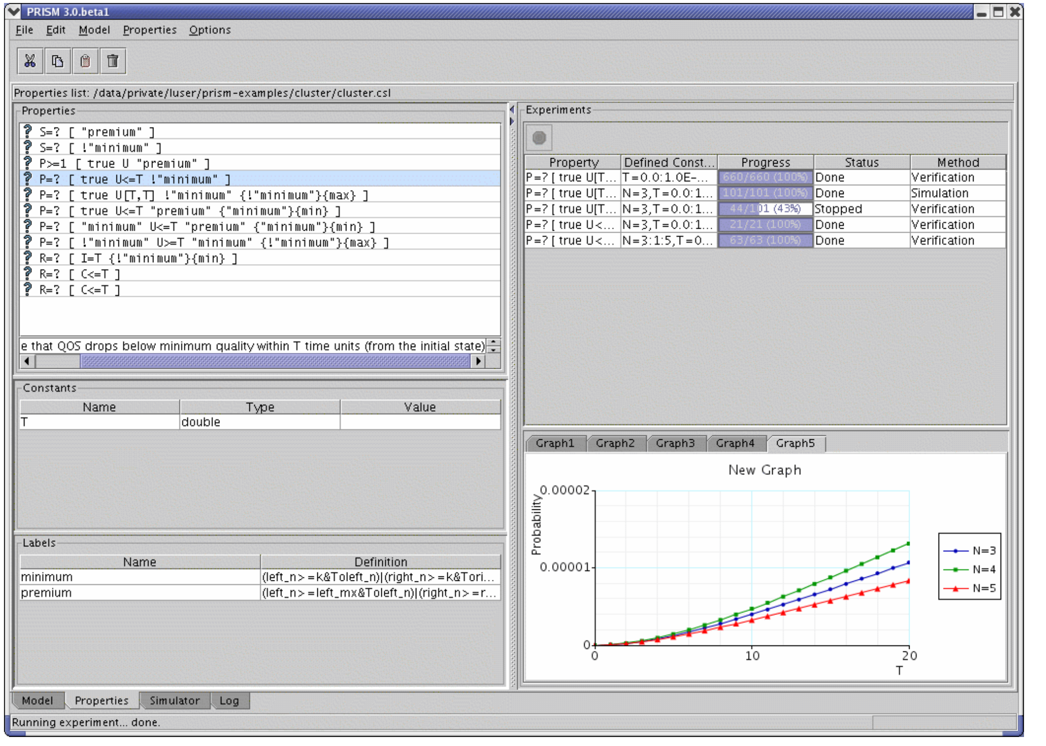

[Kwiatkowska-Norman-Parker-Segala]

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]

[KNP00] Marta Z. Kwiatkowska, Gethin Norman, and David Parker. Verifying Randomized Distributed Algorithms with PRISM. In E. Allen Emerson and A. Prasad Sistla, editors, *Workshop on Advances in Verification (Wave'2000), Chicago, USA*, 2000.

[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.

[KNP05] Marta Z. Kwiatkowska, Gethin Norman, and David Parker. Probabilistic model checking in practice: case studies with PRISM. *SIGMETRICS Performance Evaluation Review*, 32(4):16–21, 2005.

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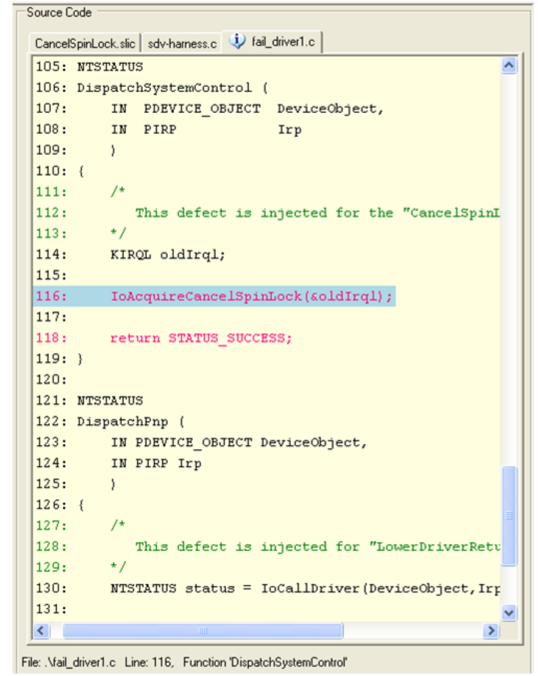

[Ball-Bounimova-Chaki-Kumar-Levin-Lichtenberg-Rajamani]

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

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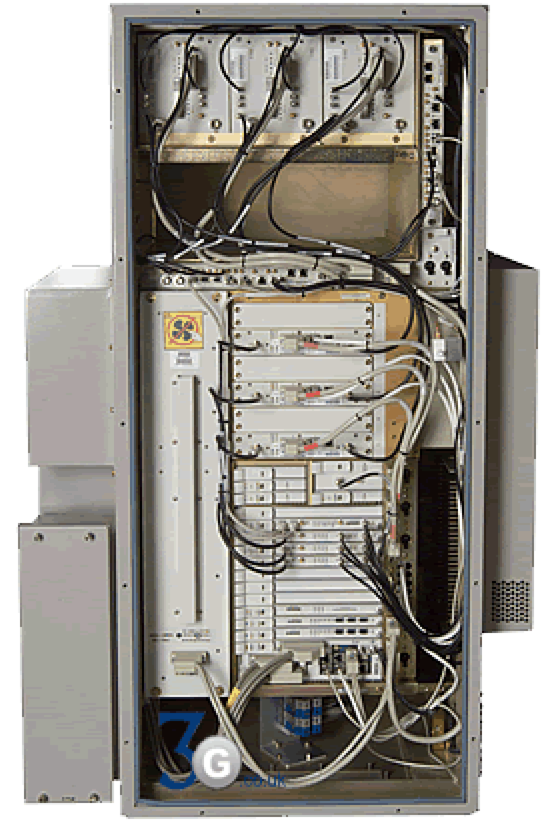

Automated analysis of Lucent's CDMA base station call-processing software library (100,000s lines of C/C++ code) using the VeriSoft tool for systematic state space exploration

Detection of several critical bugs

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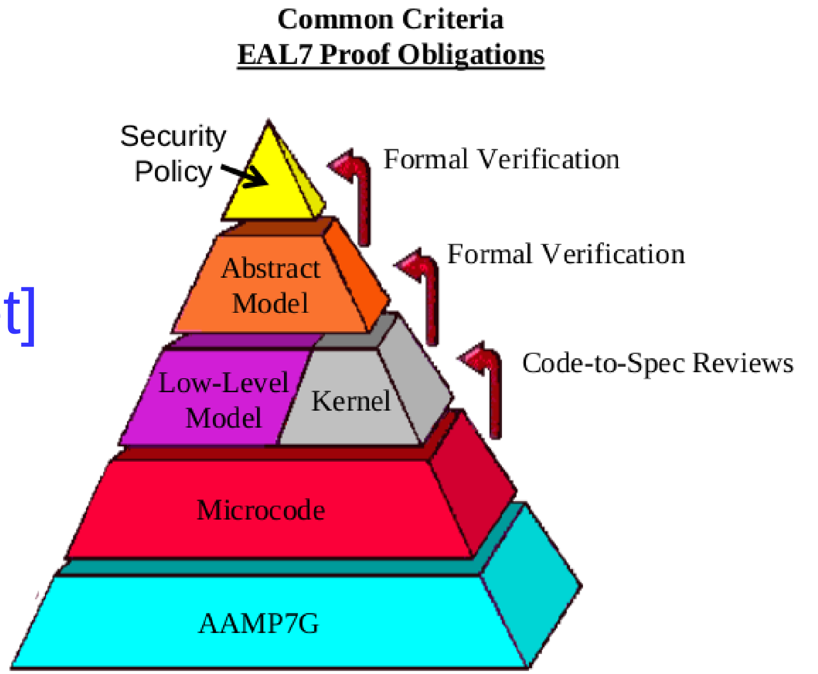
[Greve-Richards-Wilding-Vanfleet]
[Hardin-Smith-Young]



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

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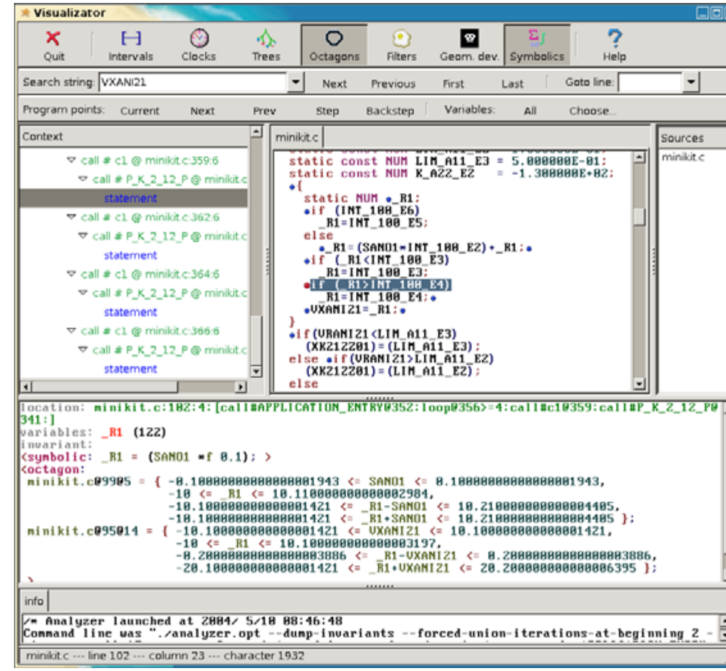

[Blanchet-Cousot-Cousot-Feret-Mauborgne-Miné-Monniaux-Rival] [Delmas-Sourys]

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

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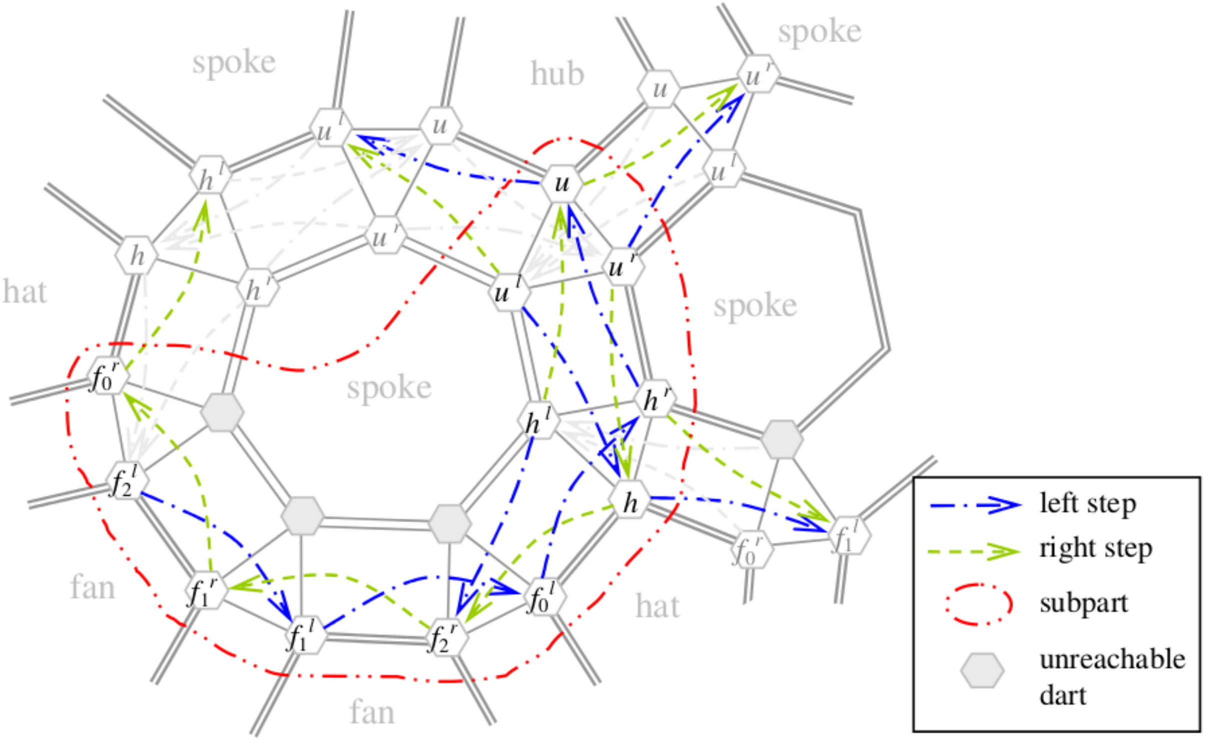

[Gonthier]

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

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2006

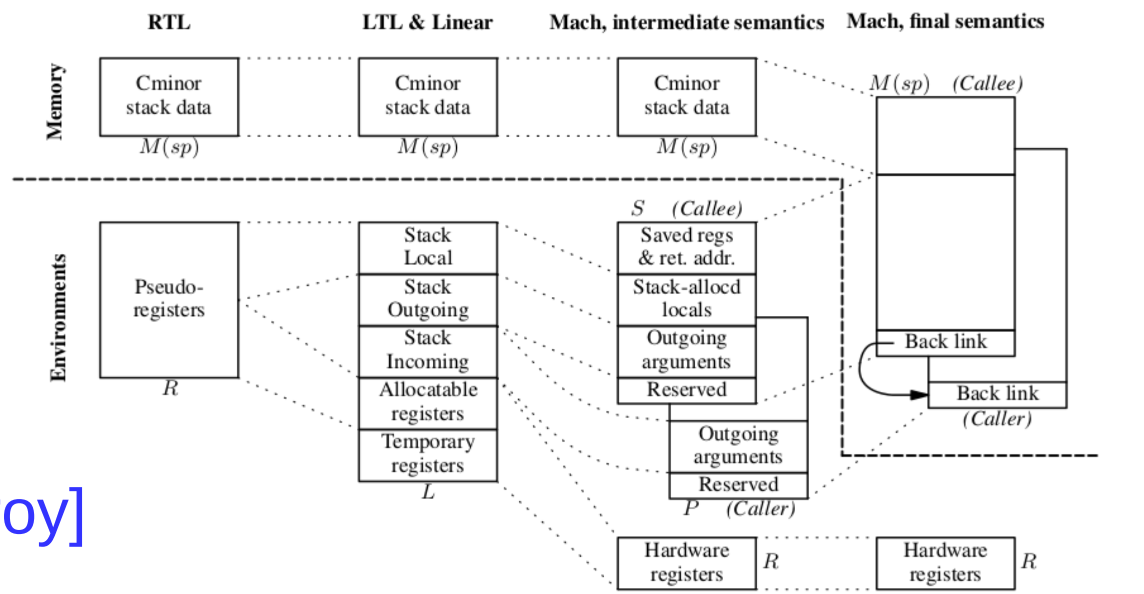

Figure 1. Overview of register allocation and introduction of activation records. For each intermediate language, the placement of function-local data is outlined, either in the memory-allocated activation record (top part) or in non memory-resident execution environments (bottom part).

[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

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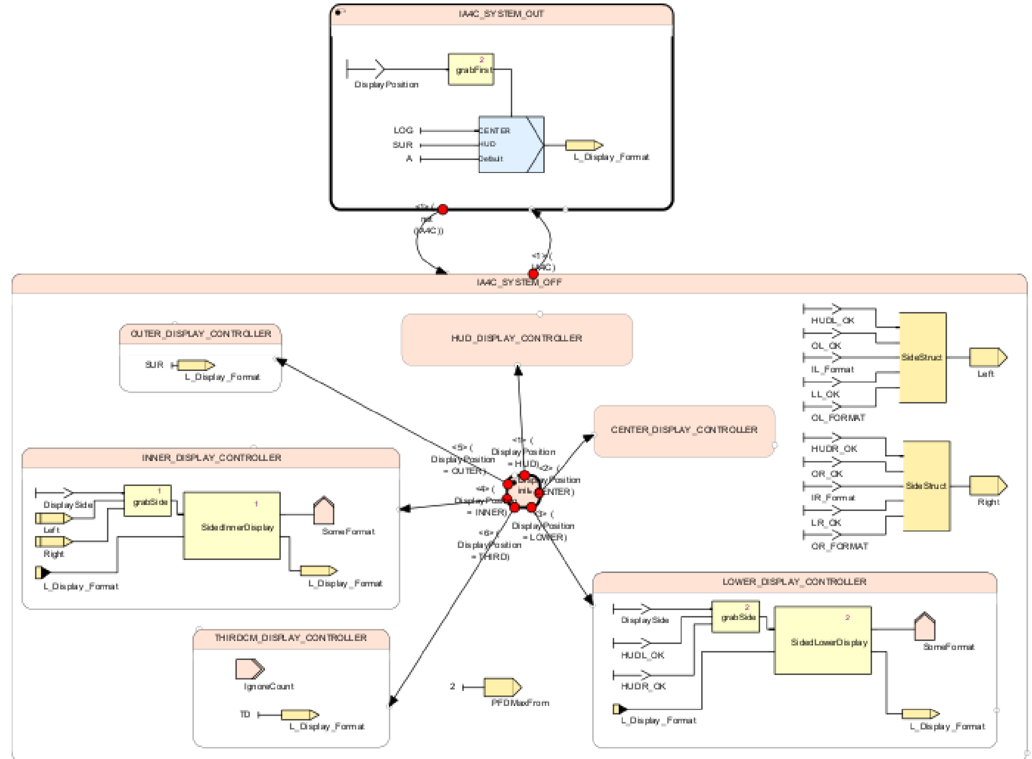

[Berry]
[Halbwachs-Caspi-Raymond-Pilaud]

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

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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

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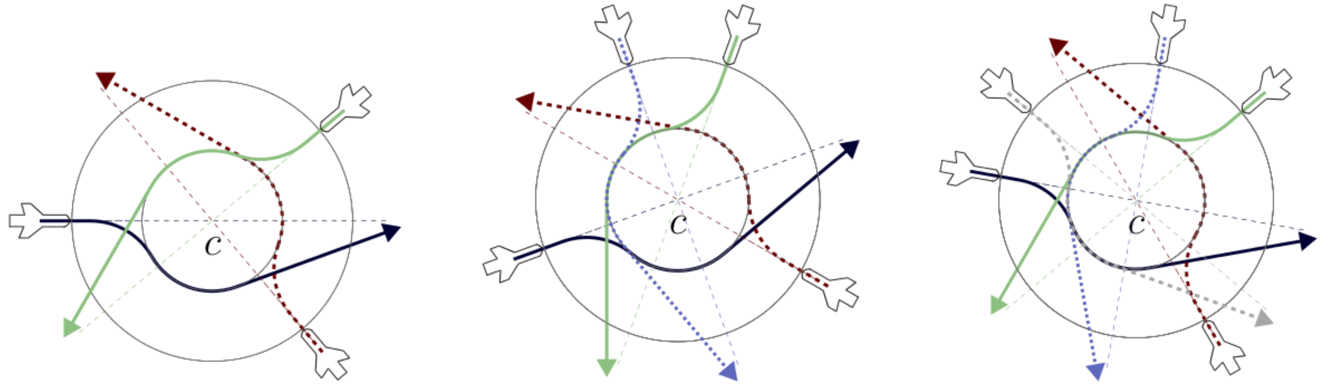

Figure 8: Flyable aircraft roundabout (multiple aircraft)

[Platzer-Clarke]

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

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[PC09a] André Platzer and Edmund M. Clarke. Computing differential invariants of hybrid systems as fixedpoints. *Formal Methods in System Design*, 35(1):98–120, 2009.

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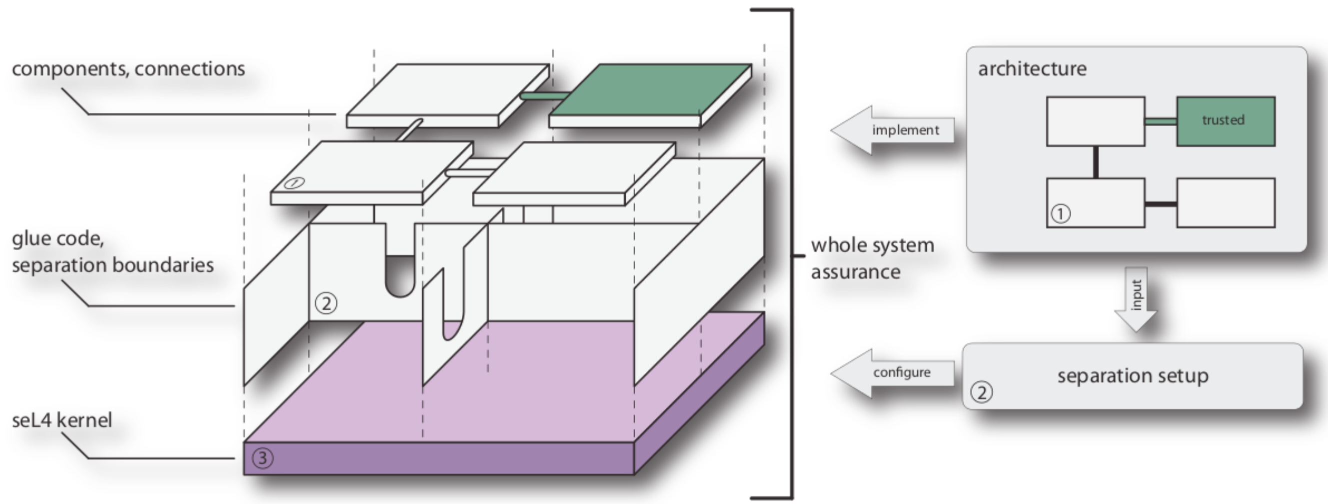

Figure 3: seL4-based system with multiple independent levels of assurance

[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]

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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