# ETMF 2023 – FORMAL METHODS: WHAT ARE THEY? WHAT ARE THEY USED FOR?

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Research interests: formal methods (theory and practice)

**CIn-TRUST**

trust.cin.ufpe.br

cin.ufpe.br/~ghpc

ROBOSTAR

robostar.cs.york.ac.uk


Project: **RoboTIC@**

ines.org.br/projects-2

**RoboWorld**: more information (publications, examples, tool, etc.)

robostar.cs.york.ac.uk/roboworld

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# A connected (software-based) society

Software and systems should behave as expected

But, do we trust them?

Formal methods to the rescue!

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# Small digression: aeroplanes

Source: https://ccntservice.airbus.com/apps/cockpits/a380


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# Small digression: aeroplanes

KLM cockpit tales: https://www.youtube.com/watch?v=XXMO1nnlnxs


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# Small digression: aeroplanes

Flight tests: https://www.youtube.com/playlist?list=PLjl-u2y72YNwiW9CQ1Tp6yOsR-WkL_QIX


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# Formal methods

What about the rigour in:
software system specification, design, and verification?

# Formal methods

What about the rigour in:
software system specification, design, and verification?

> "*Formal methods are mathematical approaches to software and system development which support the* ***rigorous*** *specification, design and verification of computer systems.*"
>
> Formal Methods Europe – FME

An important role on achieving high trustworthiness levels

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# Formal methods: not only about aeroplanes

**AWS**: How Amazon web services uses formal methods
https://doi.org/10.1145/2699417

**Google**: Using Formal Methods at Google
https://datatracker.ietf.org/meeting/118/session/ufmrg

**Meta**: Moving Fast with Software Verification
https://doi.org/10.1007/978-3-319-17524-9_1

**Microsoft**: SMT in Verification, Modeling, and Testing at Microsoft
https://doi.org/10.1007/978-3-642-39611-3_3

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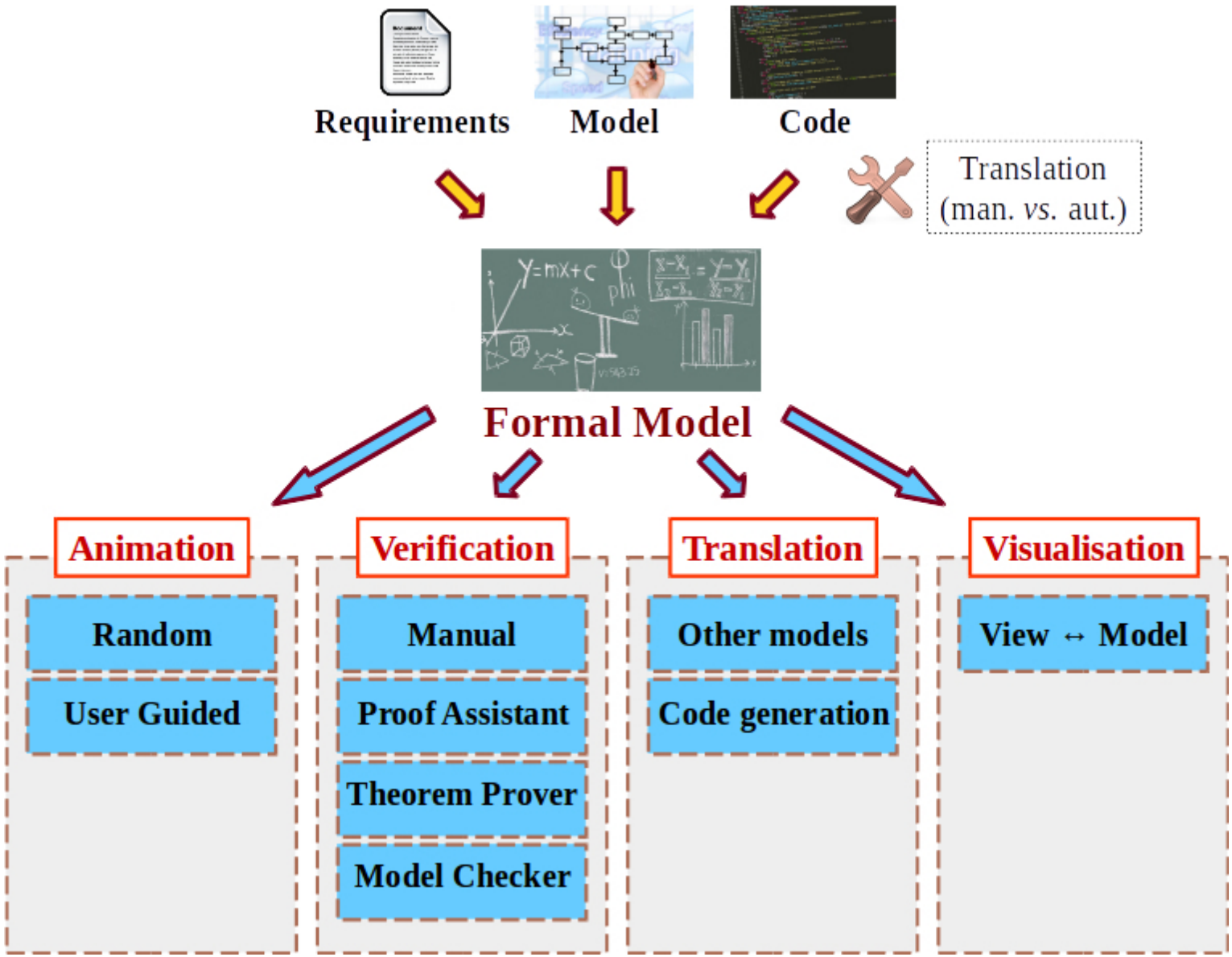
# Formal methods: a big picture



# Agenda



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# B language

Focus: safety-critical software (single threaded)

Application: numerous applications, particularly in the railway domain (https://link.springer.com/chapter/10.1007/978-3-030-58298-2_8)

Tools

- Atelier B: https://atelierb.eu/
- ProB: https://prob.hhu.de/w/index.php
- BMotionWeb: https://prob.hhu.de/w/index.php?title=BMotionWeb

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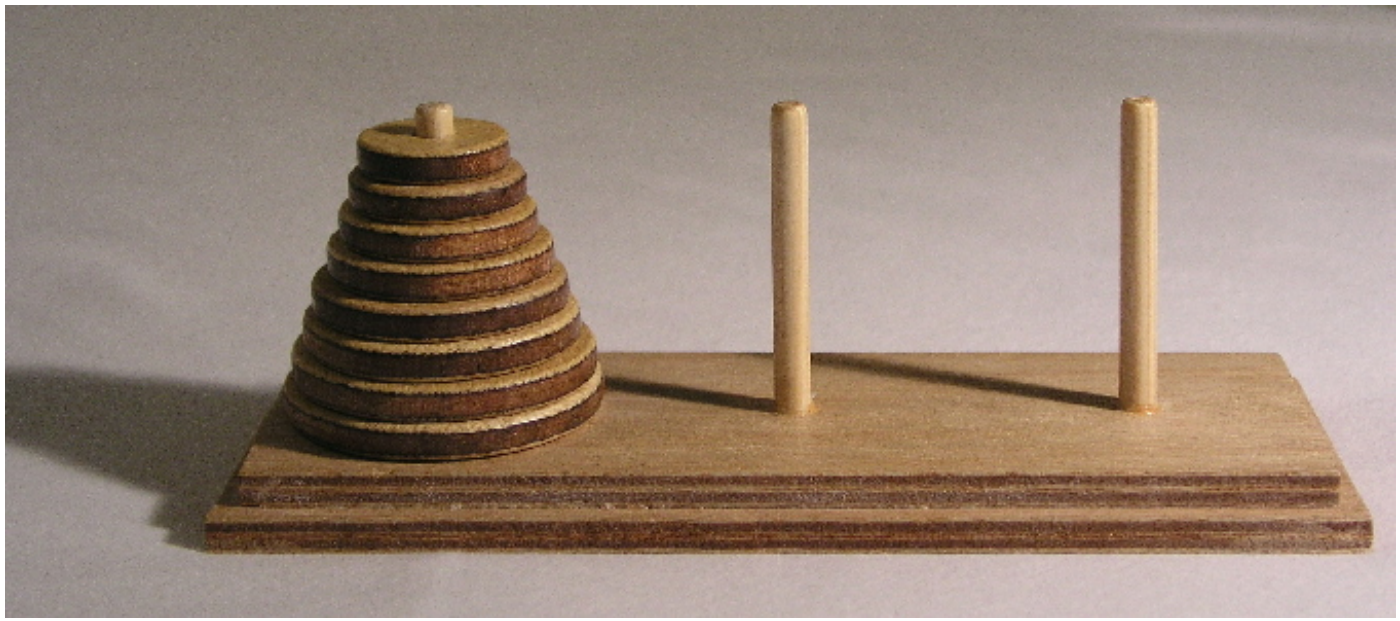
# B language: example

Tower of Hanoi puzzle[1]



[1] Source: Wikimedia Commons

# B language: specification

```
 7- VARIABLES
 8      hanoi
 9- INVARIANT
10      // System state is described as a function from pegs (1..3) to disks (1..3)
11      // 1 denotes the smaller disk, whereas 3 denotes the biggest one
12      hanoi : 1..3 --> POW(1..3)
13      // There is no disk repetition between pegs
14      & ! (p1,p2) . ((p1 : dom(hanoi) & p2 : dom(hanoi) & p1 /= p2 => hanoi(p1) /\ hanoi(p2) = {}))
15      // Is there a solution?
16      & not((hanoi(1) = {}) & (hanoi(2) = {}) & (hanoi(3) = 1..3))
17- INITIALISATION
18      // Initially, all disks on the first peg
19      hanoi := {1 |-> {1,2,3}, 2 |-> {}, 3 |-> {}}
20- OPERATIONS
21      // Moving disks between pegs
22      move(from,to) =
23-     PRE
24          // The source and target pegs shall be different
25          from : dom(hanoi) & to : dom(hanoi) & from /= to
26          // The source peg is not empty
27          & hanoi(from) /= {}
28          // You cannot place a bigger disk over a smaller one
29          & (hanoi(to) /= {} => min(hanoi(from)) < min(hanoi(to)))
30-     THEN
31          hanoi := hanoi <+
32                   // Updating the state of the source and target pegs
33-                {
34                     from |-> (hanoi(from) - {min(hanoi(from))}),
35                     to |-> (hanoi(to) \/ {min(hanoi(from))})
36                   }
37      END
```

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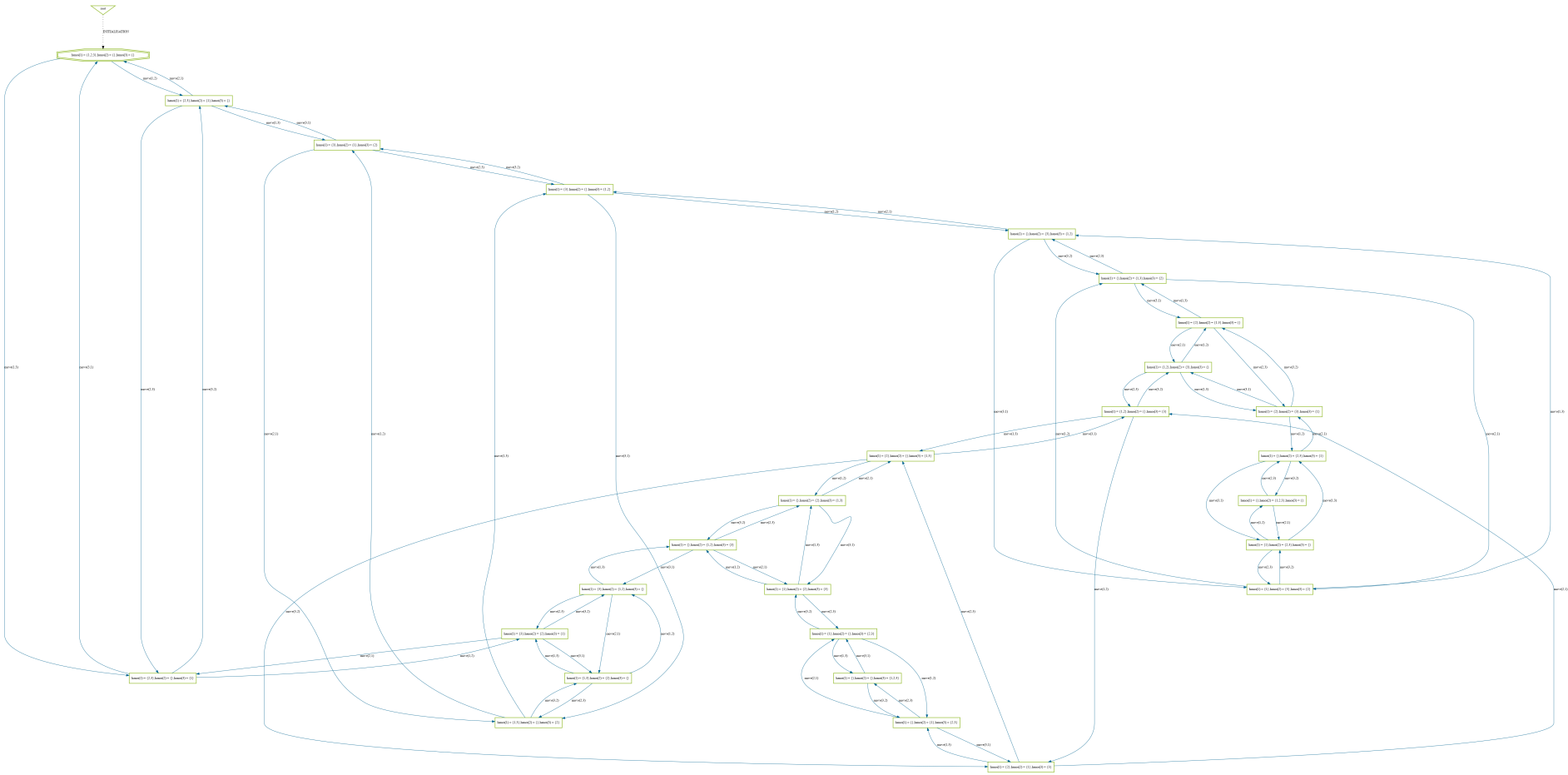
# B language: state space



28 states and 79 transitions
Graph generated with ProB

```
$ dot -Tpng Hanoi.dot > Hanoi.png
```

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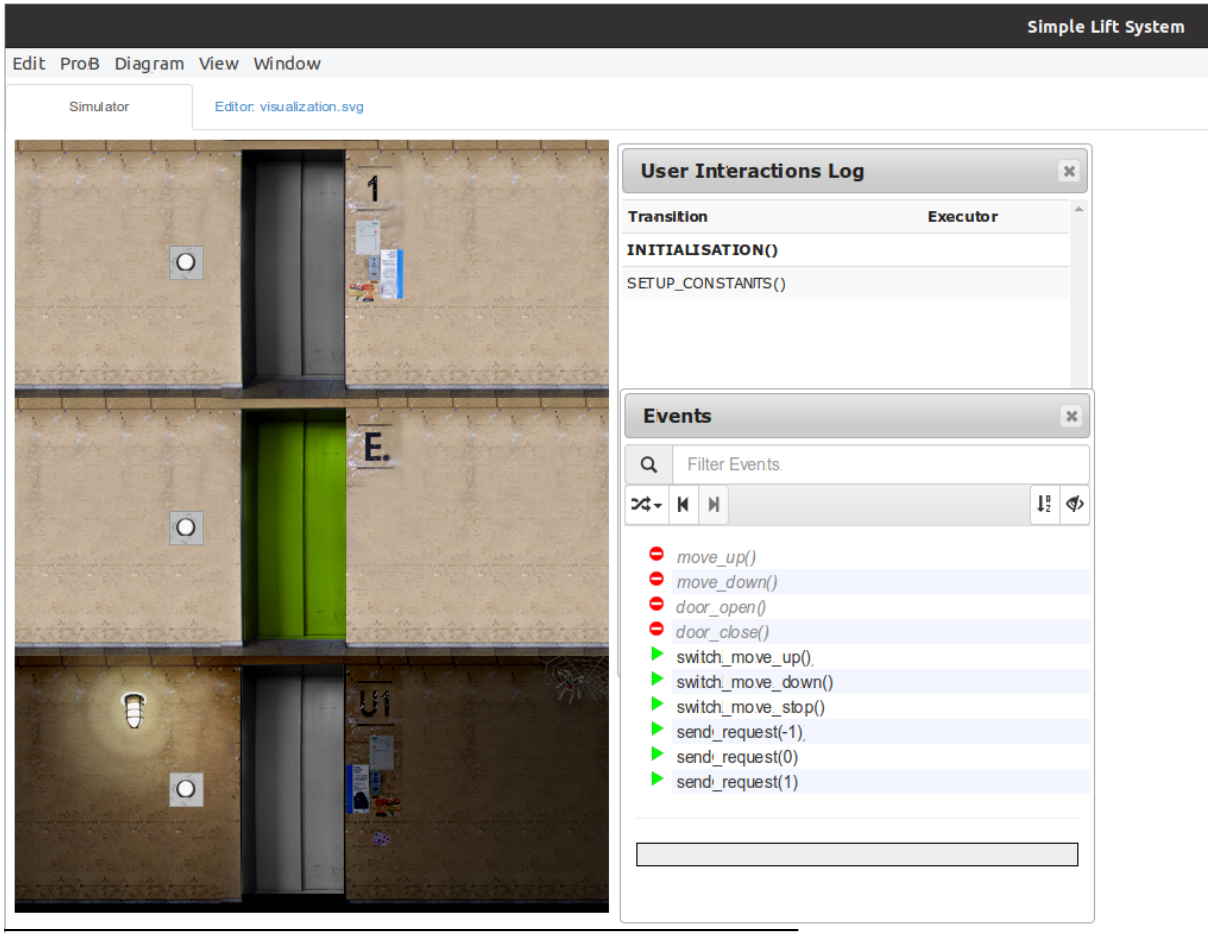
# B language: visualisation

Another example: lift[2]




[2]Source: BMotionWeb examples

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# CSP

Focus: concurrent systems

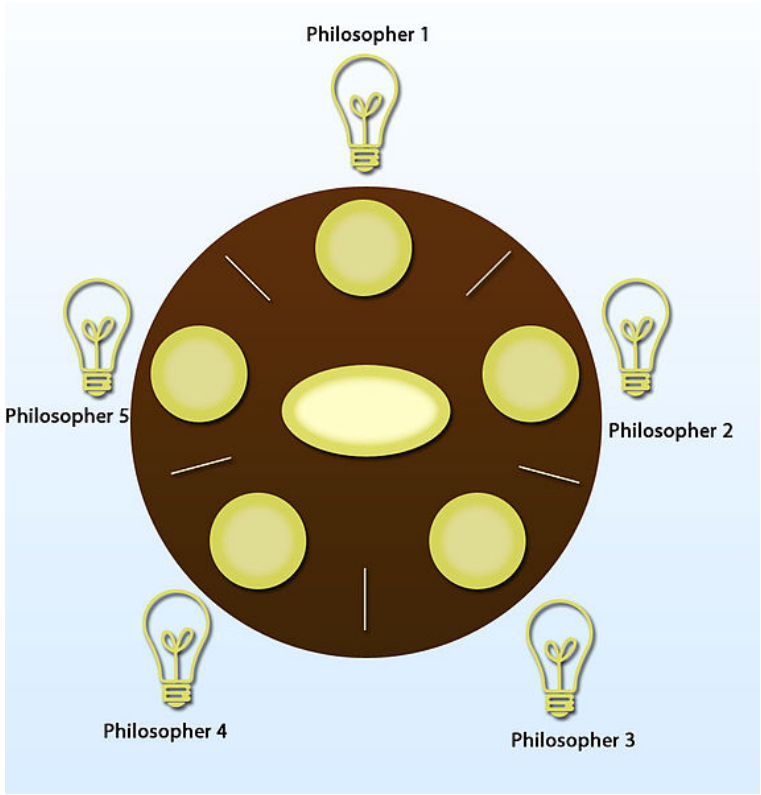
Application: numerous applications
(https://doi.org/10.1007/978-3-319-51046-0_4)

Tools

- FDR: https://cocotec.io/fdr/

# CSP: example

## Dining philosophers problem[3]



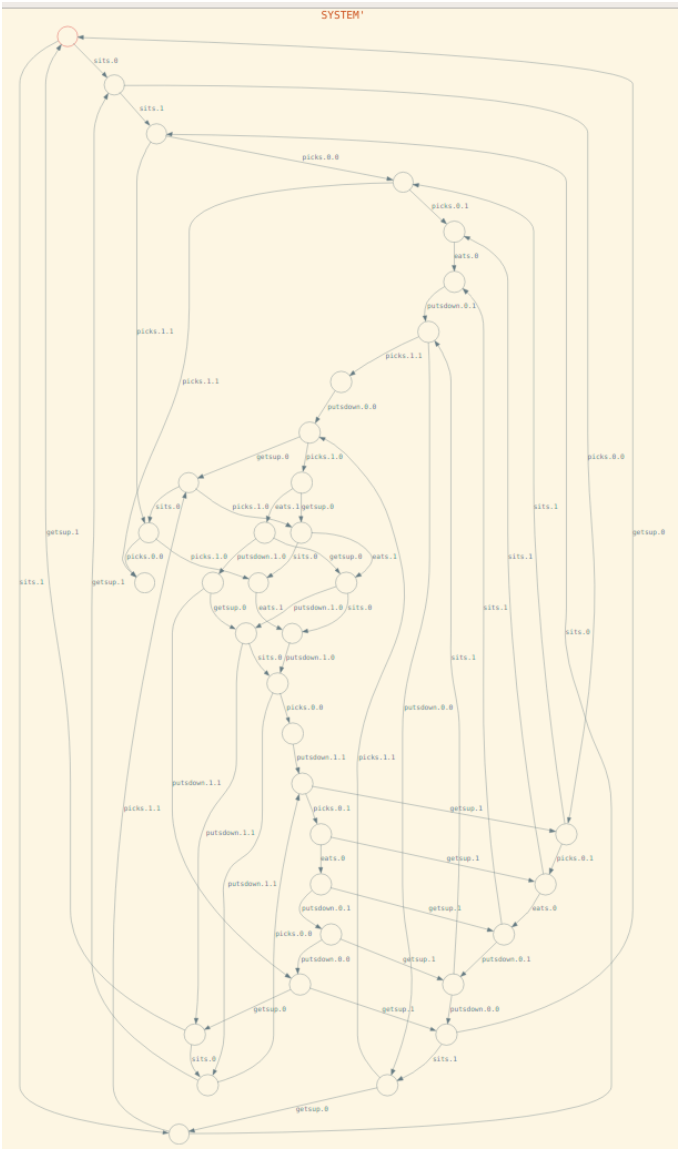

[3] Source: Wikimedia Commons

# CSP: specification[4]

```
1  -- Bill Roscoe
2  N = 4
3
4  PHILNAMES= {0..N-1}
5  FORKNAMES = {0..N-1}
6
7  channel sits, eats, getsup : PHILNAMES
8  channel picks, putsdown : PHILNAMES.FORKNAMES
9
10 PHIL(i) = sits!i -> picks!i!i -> picks!i!((i+1)%N) ->
11           eats!i -> putsdown!i!((i+1)%N) -> putsdown!i!i -> getsup!i -> PHIL(i)
12
13 FORK(i) = picks!i!i -> putsdown!i!i -> FORK(i)
14          []  picks!((i-1)%N)!i -> putsdown!((i-1)%N)!i -> FORK(i)
15
16 PHILS = ||| i:PHILNAMES @ PHIL(i)
17 FORKS = ||| i:FORKNAMES @ FORK(i)
18
19 SYSTEM' = PHILS[|{|picks, putsdown|}|]FORKS
20
21 -- The potential for deadlock is illustrated by
22
23 assert SYSTEM' :[deadlock free [F]]
24
```

[4] Code from FDR Documentation

# CSP: state space




N = 2

- States: 36
- Transitions: 65

N = 3

- States: 214
- Transitions: 565

N = 4

- States: 1,296
- Transitions: 4,569

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# Timed automata

Focus: timed systems

Application: numerous applications
(https://uppaal.org/casestudies/)

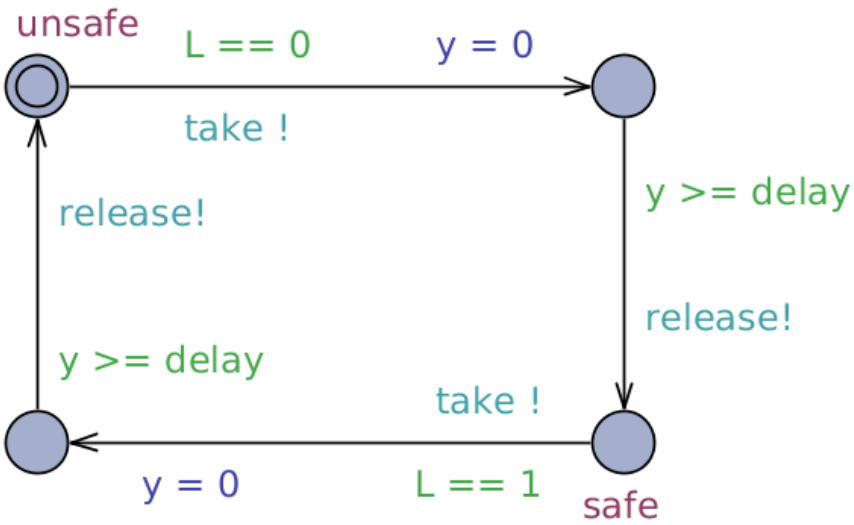
Tools

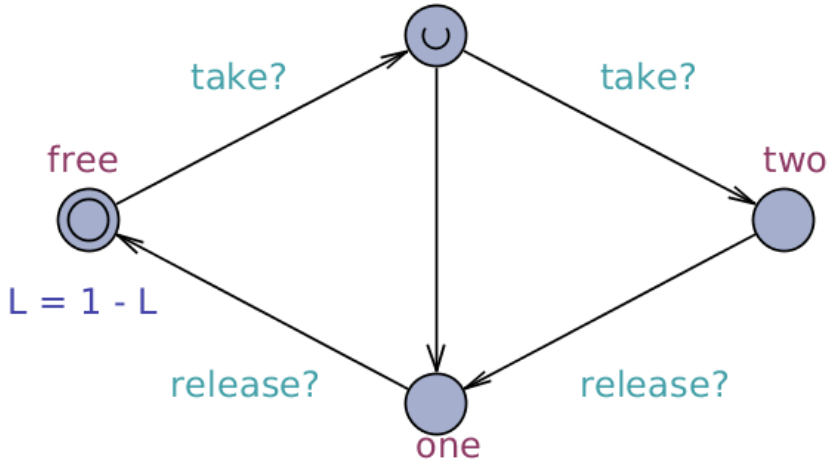
- UPPAAL: https://uppaal.org/

# Timed automata: example

Bridge crossing puzzle (Vikings version)

# Timed automata: specification[5]




[5] Source: UPPAAL demos

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# SMT-LIB v2

"*SMT-LIB is an international initiative aimed at facilitating research and development in Satisfiability Modulo Theories (SMT).*"

Focus: determining whether a mathematical formula is satisfiable
(https://en.wikipedia.org/wiki/Satisfiability_modulo_theories)

Application: numerous applications

Tools: numerous tools

- Z3:
  www.microsoft.com/en-us/research/project/z3-3/

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# SMT-LIB v2: example

$$3x + 2y = 6$$
$$2x - 3y + 5$$

```
(declare-const x Real)
(declare-const y Real)
(assert (= (+ (* 3 x) (* 2 y)) 6))
(assert (= (- (* 2 x) (* 3 y)) 5))
(check-sat)
(get-model)
(exit)
```

**Output**:

```
sat
(
  (define-fun y () Real (- (/ 3.0 13.0)))
  (define-fun x () Real (/ 28.0 13.0))
)
```

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# SMT-LIB v2: example

$$(p \Rightarrow q) \wedge (q \Rightarrow p)$$
$$\neg\,(p = q)$$

```
(declare-const p Bool)
(declare-const q Bool)
(assert (and (=> p q) (=> q p)))
(assert (not (= p q)))
(check-sat)
(exit)
```

**Output**:

```
unsat
```

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# Gallina

Focus: general purpose specification language

Application: numerous applications

(DeepSpec: https://deepspec.org/main)

Tools

- Coq proof assistant: https://coq.inria.fr/

# Gallina: example

Implementing dictionary ADT using binary search trees

```
1  clear      : dictionary -> dictionary
2  is_empty   : dictionary -> bool
3  size       : dictionary -> nat
4  insert     : key -> val -> dictionary -> dictionary
5  find       : key -> dictionary -> option val
```

# Gallina: specification, implementation and proofs

```
21 Module Type Dictionary.
22
23   (* [key]: the type of keys *)
24   Definition key              := nat.
25   (* [val]: the type of values *)
26   Definition val              := string.
27   (* [dictionary]: the type of dictionaries *)
28   Parameter dictionary        : Type.
29   (* [empty_dictioanry]: definition of an empty dictionary *)
30   Parameter empty_dictionary  : dictionary.
31
32 (**
33   Operations suppoted: [clear], [is_empty],
34                        [size], [insert], [find]
35 *)
36
37   Parameter clear     : dictionary -> dictionary.
38   Parameter is_empty  : dictionary -> bool.
39   Parameter size      : dictionary -> nat.
40   Parameter insert    : key -> val -> dictionary -> dictionary.
41   Parameter find      : key -> dictionary -> option val.
```

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# Conclusion

Mathematical approaches to support the **rigorous** specification, design and verification of computer systems

In this talk:

- B language: Atelier B, ProB, BMotionWeb
- CSP: FDR4
- Timed automata: UPPAAL
- SMT-LIB v2: Z3
- Gallina: Coq

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# Recommended reading: papers

**Formal methods in dependable systems engineering: a survey of professionals from Europe and North America**
Mario Gleirscher, Diego Marmsoler.
Empirical Software Engineering 25, pages 4473–4546. Springer 2020.

**The 2020 Expert Survey on Formal Methods**
Hubert Garavel, Maurice H. ter Beek, Jaco van de Pol.
Proc. Formal Methods for Industrial Critical Systems (FMICS 2020).
LNCS 12327, Springer 2020

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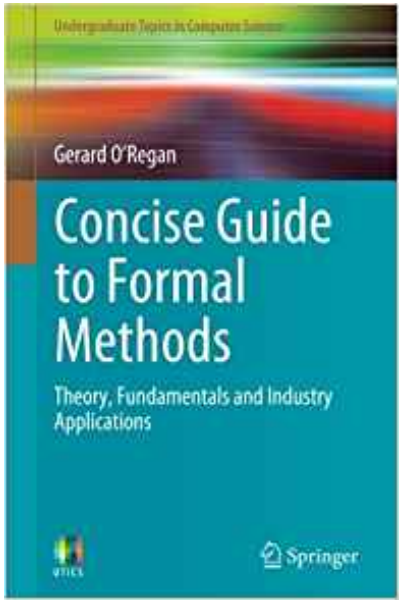
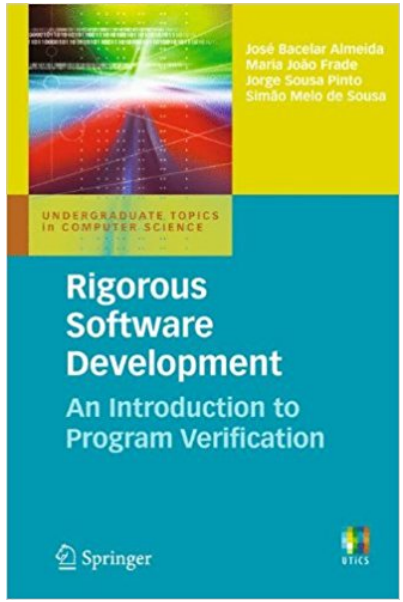
# Recommended reading: books




**Gerard O'Regan**
*Concise Guide to Formal Methods*
Springer, 2017.




**José Almeida et al.**
*Rigorous Software Development*
Springer, 2011.

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