Variability meets Security

Quantitative Security Modeling and Analysis of Highly Customizable Attack Scenarios

Maurice ter Beek
Formal Methods and Tools lab, ISTI–CNR, Pisa, Italy

Axel Legay	Alberto Lluch Lafuente	Andrea Vandin
UCLouvain, BE	DTU, DK	Sant'Anna, Pisa, IT

VaMoS 2020
Magdeburg, Germany
5 February 2020

Outline

Variability meets Security

- QFLan framework spin-off

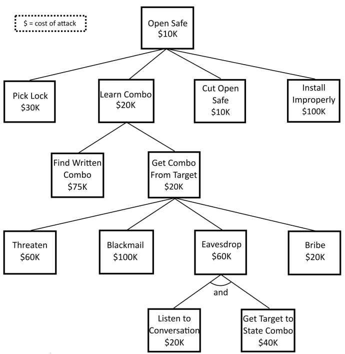
Domain Specific Language (DSL) and tool

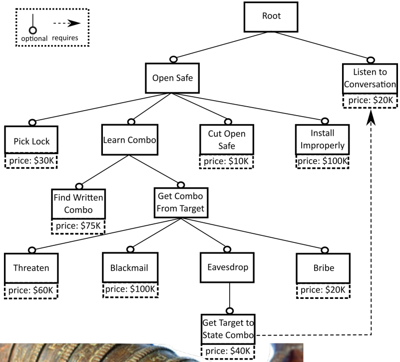
- Configurable attack-defense diagrams
- Probabilistic attack behavior
- Quantitative SMC analysis (over time)

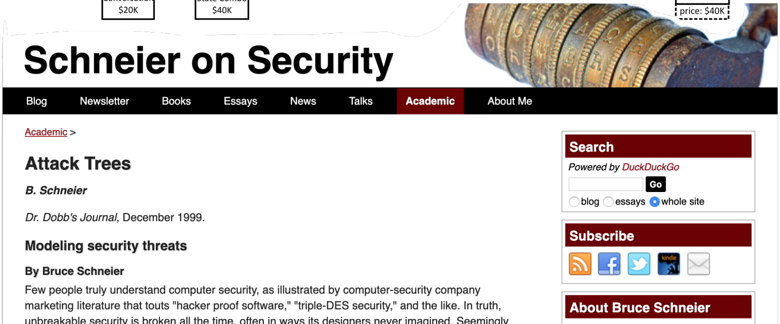
Conclusion

Vision and Roadmap

Schneier's seminal safe lock scenario







Schneier on Security

Blog | Newsletter | Books | Essays | News | Talks | Academic | About Me

Academic >

Attack Trees

B. Schneier

Dr. Dobb's Journal, December 1999.

Modeling security threats

By Bruce Schneier

Few people truly understand computer security, as illustrated by computer-security company marketing literature that touts "hacker proof software," "triple-DES security," and the like. In truth, unbreakable security is broken all the time, often in ways its designers never imagined. Seemingly

Search

Powered by *DuckDuckGo*

Go

blog essays whole site

Subscribe

About Bruce Schneier

QFLan spin-off

[TSE18] Maurice ter Beek, Axel Legay, Alberto Lluch Lafuente, and Andrea Vandin, A framework for quantitative modeling and analysis of highly (re)configurable systems. *IEEE Transactions on Software Engineering*, 2018.

[FM18] Andrea Vandin, Maurice ter Beek, Axel Legay, and Alberto Lluch Lafuente, A Tool for the Quantitative Analysis of Highly Reconfigurable Systems. *FM'18: 22nd International Symposium on Formal Methods*.

[MSc18] Christian Toftemann Bæk and Christian Bach, A Framework for Quantitative Security Modeling and Analysis of Customizable Attack Scenarios. Master's thesis, Technical University of Denmark, 2018.

[SPLC15] Maurice ter Beek, Axel Legay, Alberto Lluch Lafuente, and Andrea Vandin, Statistical Analysis of Probabilistic Models of Software Product Lines with Quantitative Constraints. *SPLC'15: 19th International Software Product Line Conference*.

Variability meets Security

- Apply variability modeling and analysis techniques to security (attack trees $\approx$ feature diagrams)
- Overall aim:
  - Graphical representations for attack scenarios (set of products)
  - Analyse the feasibility of an attack scenario on a specific system
- This paper:
  - Illustrate DSL + tool on example scenario from security domain
  - DSL syntax + semantics and tool details in forthcoming papers
- Highly customizable attack scenarios
- Types of quantitative analysis (SMC):
  - Average cost and probability of success of attacks
  - Effectiveness of defenses and countermeasures
- Conclude with a vision and roadmap for future research

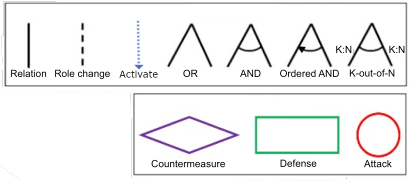
Variability meets Security

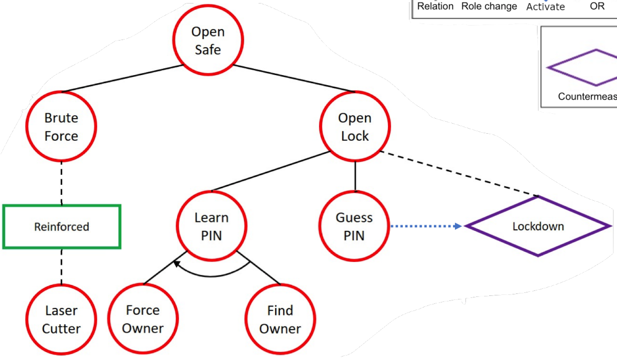
- Apply variability modeling and analysis techniques to security (attack trees $\approx$ feature diagrams)
- Overall aim:
  - Graphical representations for attack scenarios (set of products)
  - Analyse the feasibility of an attack scenario on a specific system
- This paper:
  - Illustrate DSL + tool on example scenario from security domain
  - DSL syntax + semantics and tool details in forthcoming papers
- Highly customizable attack scenarios
- Types of quantitative analysis (SMC):
  - Average cost and probability of success of attacks
  - Effectiveness of defenses and countermeasures
- Conclude with a vision and roadmap for future research

Variability meets Security

- Apply variability modeling and analysis techniques to security (attack trees $\approx$ feature diagrams)
- Overall aim:
  - Graphical representations for attack scenarios (set of products)
  - Analyse the feasibility of an attack scenario on a specific system
- This paper:
  - Illustrate DSL + tool on example scenario from security domain
  - DSL syntax + semantics and tool details in forthcoming papers
- Highly customizable attack scenarios
- Types of quantitative analysis (SMC):
  - Average cost and probability of success of attacks
  - Effectiveness of defenses and countermeasures
- Conclude with a vision and roadmap for future research

Schneier's safe lock extended

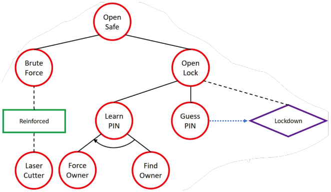




Equip attack trees with defenses and countermeasures and behavior (attack-defense diagrams)

- Attack nodes need to be explicitly activated by attack behavior
- Static defenses and dynamic countermeasures

DSL: attack, defense, and countermeasure nodes

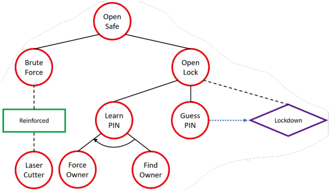



```
begin attack nodes
 OpenSafe BruteForce OpenLock GuessPIN LearnPIN
 FindOwner ForceOwner LaserCutter
end attack nodes

begin defense nodes
 Reinforced
end defense nodes

begin countermeasure nodes
 Lockdown = { GuessPIN }
end countermeasure nodes
```

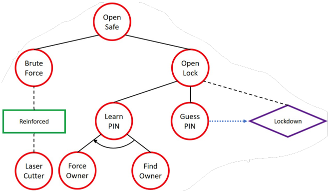
DSL: hierarchical relations




```
begin attack diagram
 OpenSafe -> { BruteForce, OpenLock }
 OpenLock -> { GuessPIN, LearnPIN }
 LearnPIN -OAND-> [ FindOwner, ForceOwner ]
 BruteForce -> { Reinforced }
 Reinforced -> { LaserCutter }
 OpenLock -> { Lockdown }
end attack diagram
```

- Defense nodes cannot be refined
- Countermeasures can be refined: reactive defense nodes become effective upon (attack detection and) countermeasure activation

DSL: attributes

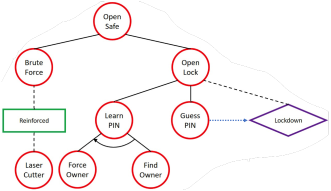



```
begin attributes
 Cost = { LaserCutter = 200, FindOwner = 20,
          ForceOwner = 10, Reinforced = 250 }
end attributes
```

- Attributes like cost or detection rate allow quantitative analysis and to impose constraints, like the maximum cost

  (default value is 0, i.e. Cost(GuessPIN) = 0)
- Also for defense nodes

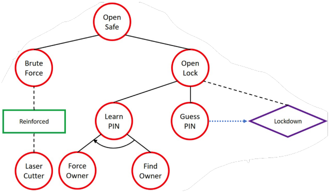
DSL: attack detection rates




```
begin attack detection rates
 BruteForce = 0.5, OpenLock = 0.1, GuessPIN = 0.8,
 LearnPIN = 0.3, FindOwner = 0.6, ForceOwner = 0.7,
 LaserCutter = 0.6
end attack detection rates
```

- Determine the probability for attack attempts to be detected; attack attempt is the execution of `succ(·)` or `fail(·)` action (default value is 0, i.e. an attack is undetectable)
- Detection triggers the activation of affected countermeasures; higher detection rates mean more likely activations

DSL: defense effectiveness



(ALL denotes any attacker)

```
begin defense effectiveness
 Reinforced(ALL, BruteForce) = 0.95
 Lockdown(ALL, OpenLock) = 0.8
end defense effectiveness
```

- In security nothing is ever 100% secure: specify effectiveness of a defensive node against any combination of attack nodes and attack behavior; probability of how likely an attack is thwarted (default value is 0, i.e. the defense has no effect)
- Different attackers might be affected differently by a defense, even when attempting the same attack (e.g. a security guard is effective against a thief, but not against a military attack)

DSL: (probabilistic) attack behavior

- Defensive behavior is reactive while an attacker is proactive
- Fine tune a security scenario by defining attack behavior, implicitly constrained by the attack-defense diagram
- Explicit attack behavior allows for novel types of analysis that complement the classical best- and worst-case evaluations of attack trees (e.g. bottom-up evaluation in well-known ADTool)

- QFLan spin-off: each (optional) feature of a configurable system is a node which is installed by a configurator process similarly to how attack nodes are added by an attacker

$\Rightarrow$ Extended with different types of nodes and refinement, additional notions corresponding to defense effectiveness, attack detection rates, `fail(·)` actions, transition guards

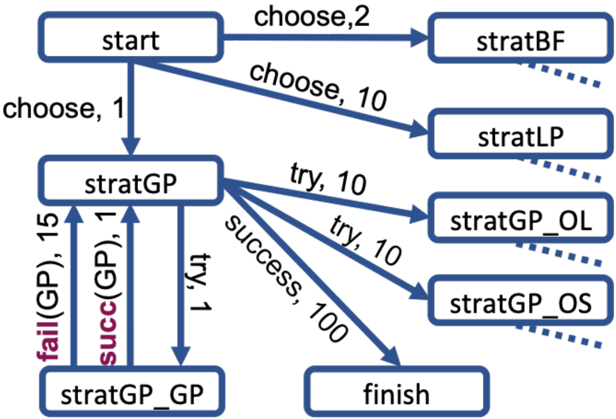
DSL: (probabilistic) attack behavior

- Defensive behavior is reactive while an attacker is proactive
- Fine tune a security scenario by defining attack behavior, implicitly constrained by the attack-defense diagram
- Explicit attack behavior allows for novel types of analysis that complement the classical best- and worst-case evaluations of attack trees (e.g. bottom-up evaluation in well-known ADTool)

- QFLan spin-off: each (optional) feature of a configurable system is a node which is installed by a configurator process similarly to how attack nodes are added by an attacker

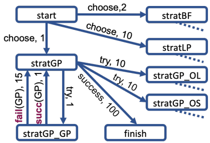
$\Rightarrow$ Extended with different types of nodes and refinement, additional notions corresponding to defense effectiveness, attack detection rates, `fail(·)` actions, transition guards

DSL: (probabilistic) attack behavior



(e.g. from `start` to `stratGP` with probability $\frac{1}{1+2+10}$)

DSL: user-defined and built-in actions



(user-defined actions)

```
begin actions
 choose try success
end actions
```

- Built-in actions, like `succ(·)` or `fail(·)`, denote the success or failure of an attack attempt
- Attack attempts are modeled by probabilistic choice between `succ(·)` and `fail(·)` actions

  Transition weights determine the success likelihood, together with (the effectiveness of) the involved defenses

DSL: hierarchical, quantitative, and action constraints

"*the accumulated cost of an attack may not exceed 250*" and
"*an attacker may not attempt more than 15 attacks*"

```
begin quantitative constraints
 { sum(Cost) < 250 }
 { AttackAttempts < 15 }
end quantitative constraints
```

"*an attacker is not allowed to attempt using a laser cutter if the cost already exceeded 100*"

```
begin action constraints
 do(succ(LaserCutter)) -> {sum(Cost) < 100}
 do(fail(LaserCutter)) -> {sum(Cost) < 100}
end action constraints
```

DSL: hierarchical, quantitative, and action constraints

"*the accumulated cost of an attack may not exceed 250*" and
"*an attacker may not attempt more than 15 attacks*"

```
begin quantitative constraints
 { sum(Cost) < 250 }
 { AttackAttempts < 15 }
end quantitative constraints
```

"*an attacker is not allowed to attempt using a laser cutter if the cost already exceeded 100*"

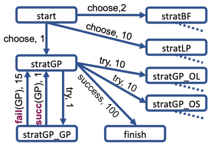
```
begin action constraints
 do(succ(LaserCutter)) -> {sum(Cost) < 100}
 do(fail(LaserCutter)) -> {sum(Cost) < 100}
end action constraints
```

DSL: real-valued variables

```
begin variables
 AttackAttempts = 0
end variables
```

- Model context information: greatly facilitates analysis phase
- Updated as side effects when executing the specification, i.e. memory updates which label transitions

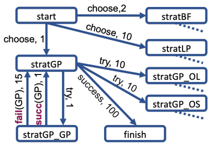
DSL: attack behavior (1/2)




```
begin attacker behavior
 begin attack
  attacker = clever
  states = start, finish, stratForce, stratF_OpenSafe,
      stratF_BruteForce, stratF_LaserCutter, stratLearnPIN,
      stratLP_OpenSafe, stratLP_OpenLock, stratLP_LearnPIN,
      stratLP_FindOwner, stratLP_ForceOwner, stratGuessPIN,
      stratGP_GuessPIN, stratGP_OpenSafe, stratGP_OpenLock
  transitions =
   //Pick a strategy:
   start -(choose,  1)-> stratGuessPIN,
   start -(choose,  2)-> stratForce,
   start -(choose, 10)-> stratLearnPIN,
   //Strategy GuessPIN:

   (continued on next slide)
```

DSL: attack behavior (2/2)




```
   (continuation of previous slide)

   //Strategy GuessPIN:
   stratGuessPIN -(try, 1, allowed(GuessPIN) and
       !has(GuessPIN))-> stratGP_GuessPIN,
   stratGP_GuessPIN -(succ(GuessPIN),  1, {AttackAttempts=
       AttackAttempts+1})-> stratGuessPIN,
   stratGP_GuessPIN -(fail(GuessPIN), 15, {AttackAttempts=
       AttackAttempts+1})-> stratGuessPIN,
   ...
   stratGuessPIN -(success, 100, has(OpenSafe))-> finish
   //Strategies Force and LearnPIN ...
 end attack
end attacker behavior
```

DSL: init

```
begin init
 clever = { FindOwner }
end init
```

- Attack behavior is completed by specifying the attacker used and pre-accomplished attacks

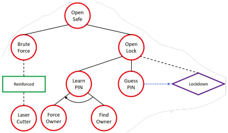
  (enriches expressiveness: assign initial advantage to attacker)

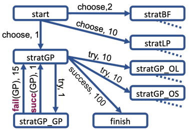
DSL: quantitative analysis

```
begin analysis
 query = eval when { AttackAttempts == 1 } : { Open-
  Safe, BruteForce, OpenLock, GuessPIN, LearnPIN, Find-
  Owner, ForceOwner, LaserCutter, steps[delta = 0.5] }
 default alpha = 0.05 delta = 0.1 parallelism = 1
end analysis
```

⇒ Probability for each attack to be attempted first and succeed plus the average steps performed to attempt the first attack?

Open Safe	Brute Force	Open Lock	Guess PIN	Learn PIN	Find Owner	Force Owner	Laser Cutter	steps
0	0.013	0	0.013	0	1	0.27	0.056	3



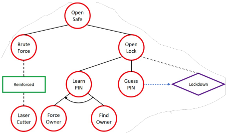


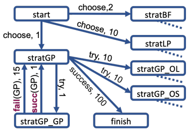
DSL: quantitative analysis

```
begin analysis
 query = eval when { AttackAttempts == 1 } : { Open-
  Safe, BruteForce, OpenLock, GuessPIN, LearnPIN, Find-
  Owner, ForceOwner, LaserCutter, steps[delta = 0.5] }
 default alpha = 0.05 delta = 0.1 parallelism = 1
end analysis
```

⇒ Probability for each attack to be attempted first and succeed plus the average steps performed to attempt the first attack?

Open Safe	Brute Force	Open Lock	Guess PIN	Learn PIN	Find Owner	Force Owner	Laser Cutter	**steps**
0	0.013	0	0.013	0	1	0.27	0.056	3



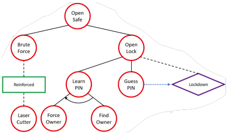


DSL: quantitative analysis (over time)

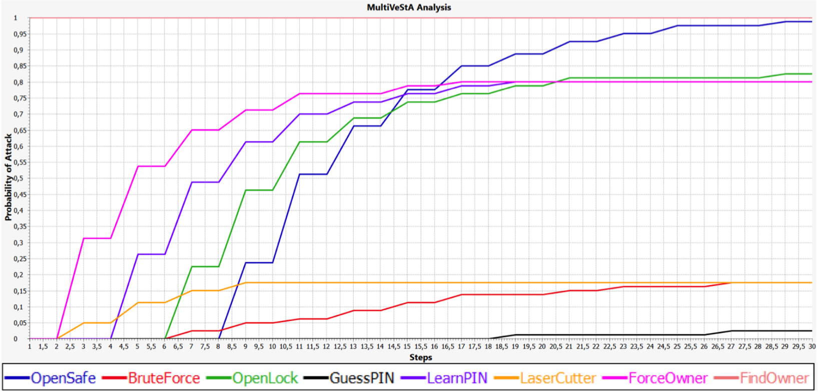
⇒ Analyse properties over time: from 9 to 500 properties!

```
begin analysis
 query = eval from 1 to 50 by 1 : { OpenSafe, Brute-
     Force, OpenLock, GuessPIN, LearnPIN, FindOwner,
     ForceOwner, LaserCutter, Lockdown, Reinforced }
 default alpha = 0.05 delta = 0.1 parallelism = 1
end analysis
```

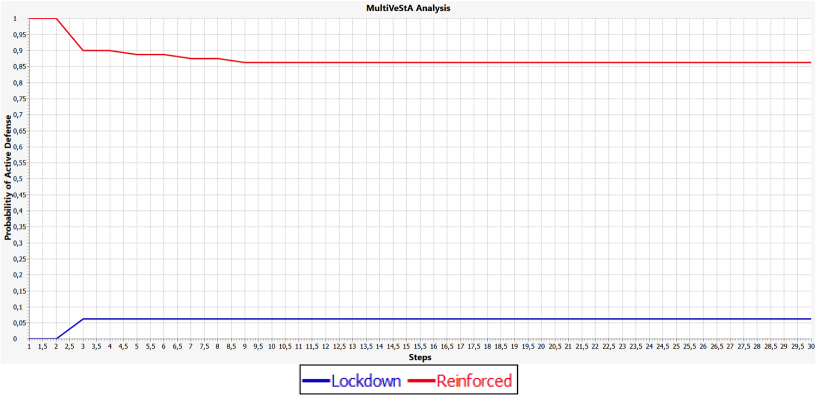
⇒ Probability for each attack that is attempted successfully and probability of activating the two defensive nodes



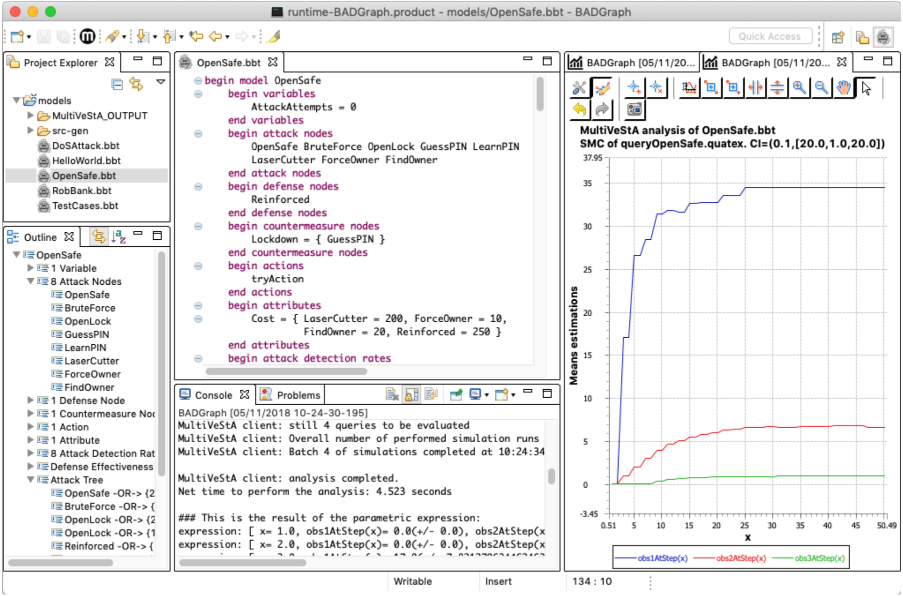
Results: probability of successful attacks (over time)



Results: probability of active defensive nodes (over time)



Tool: screenshot



Conclusion

[TSE18]:

- Integrated modeling + analysis approach for configurable systems
- Illustrated flexibility by application to a confined security scenario

⇒ limitations requiring intermediate encoding into security notions

[VaMoS20]:

- Special-purpose DSL
- Quantitative analysis

⇒ illustrate DSL + tool on example scenario from security domain

Future twin papers:

⇒ syntax and semantics

⇒ full tool presentation

Conclusion

[TSE18]:

- Integrated modeling + analysis approach for configurable systems
- Illustrated flexibility by application to a confined security scenario

$\Rightarrow$ limitations requiring intermediate encoding into security notions

[VaMoS20]:

- Special-purpose DSL
- Quantitative analysis

$\Rightarrow$ illustrate DSL + tool on example scenario from security domain

Future twin papers:

$\Rightarrow$ syntax and semantics

$\Rightarrow$ full tool presentation

Conclusion

[TSE18]:

- Integrated modeling + analysis approach for configurable systems
- Illustrated flexibility by application to a confined security scenario

⇒ limitations requiring intermediate encoding into security notions

[VaMoS20]:

- Special-purpose DSL
- Quantitative analysis

⇒ illustrate DSL + tool on example scenario from security domain

Future twin papers:

⇒ syntax and semantics

⇒ full tool presentation

Vision and Roadmap

$\Rightarrow$ more fine-grained correlation of steps (temporal logic $\diamond$ and $\square$)

- "*if an attack step (or, in fact, any step) A is performed, then defense step B is performed in less than X units of time*"

$\Rightarrow$ synthesize the best attacker (Uppaal Stratego)

- "*all attackers with feature A satisfy a given property*"

$\Rightarrow$ more generic properties by requirements in full LTL

- "*if a person has the authorization to enter and wants to enter, then (s)he will eventually enter*"

$\Rightarrow$ try to derive attackers with the best chance of success (e.g. leave some weights off the edges and rather derive them)

https://qavs.edgecloud.de/

QONFEST

Vienna, Austria

August 31 – September 5, 2020

confirmed date: 31 August 2020

Workshop QAVS'20 on Quantitative Aspects of Variant-rich Systems:

Design	of	performance	in	feature-oriented systems
Modeling		reliability		product lines
Implementation		costs		highly configurable systems
Analysis		stochastic effects		
Verification				

PC chairs: Maurice ter Beek and Clemens Dubslaff (TU Dresden, DE)

$\Rightarrow$ submission deadline: 12 June 2020

CONCUR - FMICS - FORMATS - QEST

https://fmics20.ait.ac.at/

QONFEST

Vienna, Austria
August 31 – September 5, 2020

31st CONCUR – 25th FMICS – 18th FORMATS – 17th QEST:

Theory, formal modelling, verification, performance evaluation, and engineering of concurrent, timed, and other systems . . .

New in 2020: special track on Formal Methods for Security in IoT

Thomas Henzinger | IST Austria
CONCUR | QEST | FMICS Speaker

Stefan Resch | THALES
FMICS Speaker

Roderick Bloem | TU Graz
CONCUR | FORMATS | FMICS Speaker