Formal Verification of Data-Intensive Applications through Model Checking Modulo Theories

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Big Data is everywhere!

Software market switches to Big Data: popular technologies such as Spark, Storm, Hadoop, and NoSQL stimulates Big Data adoption.

Business issue: 65% of Big Data projects still fail (Capgemini Report 2015)

Solution:
Integrating Quality Assurance (QA) practices in application development

DICE project (`http://www.dice-h2020.eu/`) aims to define methods and tools for the data-aware *quality*-driven development of Date Intensive Applications (DIAs).

Prediction of quality properties of DIAs:

- Performance, reliability, *safety properties*
- Helpful early in the DIA design
- Assess the potential impact of architectural changes (iteratively)

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Apache Storm (`storm.apache.org`) technology – used in applications that need efficient processing of unbounded streams of data, such as event log monitoring, real-time data analytics and data normalization.

Applications that use Storm: Yahoo, Twitter, Spotify, The Weather Channel, etc.

Key concepts:

- streams – infinite sequences of tuples that are processed by the application
- topologies – directed graphs
  - *nodes* represent operations performed over the application data
  - *edges* indicate how such operations are combined

Types of nodes:

- *input nodes* bring information into the application from the environment: spouts
- *computational nodes* implement the logic of the application by processing information and producing a result: bolts

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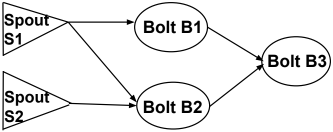

Finite state automata describing the states of a spout (left) and bolt (right)

Features of the topology:

- parametric in the number of nodes and processes
- the number of nodes is known at design-time, hence fixed

Infinite-state model checking!

Suitable abstraction: **array-based systems**. (Ghilardi et al.)

Safety verification of Storm topologies: given queue(s) bound(s) defined by the designer, “all bolt queues have a limited occupation level”.

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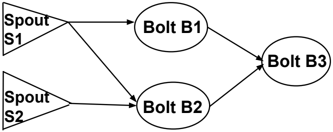

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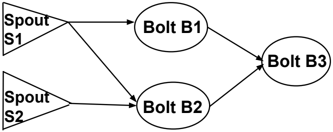

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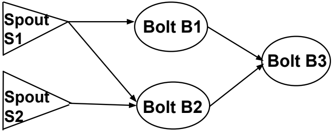

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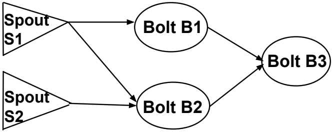

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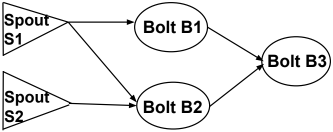

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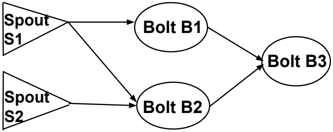

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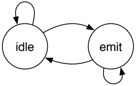

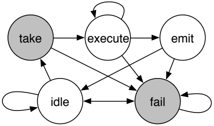

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Array-based Systems

Formalizing an array-based system means specifying:

- the set of initial states
- the ordering of the actions (by means of a transition relation)
- the set of unsafe states (the negation of the formula we want to check)

Examples (Cubicle syntax):

- `init (i x) { T = 0.0 && B[i,x]=I && ...  }` $\rightsquigarrow \underset{i,x}{\forall} \ldots$
- `transition spout_emit(i j)` $\rightsquigarrow \underset{i,j}{\exists} \ldots$

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  requires {Tsmin<Stime[i] && SubscribedBS[j,i]=True && ...}
   {
          L[l]:=case
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  ```
- `unsafe(i) { L[i]>1.5 }` $\rightsquigarrow \underset{i}{\exists} \ldots$

Symbolic representation of array-based systems: *quantified first-order logic formulae*.
Verification of array-based systems: *decision procedure* based on backward reachability.
Termination of the decision procedure:

- the current set of reachable states has a non-empty intersection with the set of initial states (safety check) ⇒ system is unsafe
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$\rightsquigarrow \underset{i,j}{\exists} \ldots$ (for `transition spout_emit(i j)`)

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- Focus on the behavior of the queues of the bolts
- How time parameters of the topology affect the accumulation of tuples in the queues of the bolts
  - Time frequency the spouts send information to the subscribed bolts, i.e. *minimum time between two consecutive spout emits*
  - Tuples processing time for each bolt, i.e. *the time required by bolts to process a tuple (execution rate)*
- Spouts are considered sources of information; their queues are not represented
- Each bolt has one receiving queue and no sending queue
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  - each bolt has one receiving queue for each of its parallel instances (multiple queues) ($L[i, x]$)
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The formalization captures the topology behavior (subscription relation, current state, modeling assumptions) through transitions:

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Challenges

- Nondeterministic updates

$$\underset{x,y,i,j}{\exists}\ \mathit{statechange} = \texttt{true}\ \wedge$$
$$\underset{l,k,z}{\forall}\begin{pmatrix} \mathit{statechange}' = & \texttt{false} \\ \ldots & \\ B'[l,z] = & \textbf{if}\ (z = y \wedge l = j \wedge B[j,y] = \texttt{E}) \\ & \textbf{then}\ (\texttt{I}\ \textbf{or}\ \texttt{K})\ \textbf{else}\ B[l,z] \\ & \textbf{elseif}\ \ldots \\ \mathit{CanTimeElapse}' = & \texttt{true} \end{pmatrix}$$

- Reducing the dimension of the search space
  - spout states were left out; only the time elapsing to enable spout `emit` is considered
  - bolt queues have only one dimension (shared queue)

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Experimental results

First attempt:

- $L[1] \geq 3$ and $Tsmin < 1$ – expected result: UNSAFE

  Trace: $Init \rightarrow time\_elapse \rightarrow setDoTake_{\texttt{False}} \rightarrow setDoEmit_{\texttt{False}} \rightarrow \mathbf{spout_{emit}} \rightarrow time\_elapse \rightarrow setDoTake_{\texttt{True}} \rightarrow setDoEmit_{\texttt{False}} \rightarrow \mathbf{bolt1_{take}} \rightarrow setDoTake_{\texttt{False}} \rightarrow setDoEmit_{\texttt{False}} \rightarrow \mathbf{spout_{emit}} \rightarrow time\_elapse \rightarrow setDoTake_{\texttt{False}} \rightarrow setDoEmit_{\texttt{False}} \rightarrow \mathbf{spout_{emit}} \rightarrow L[1] \geq 2$

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Result: the verification problems lead to memory exhaustion.

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