Dynamic Verification

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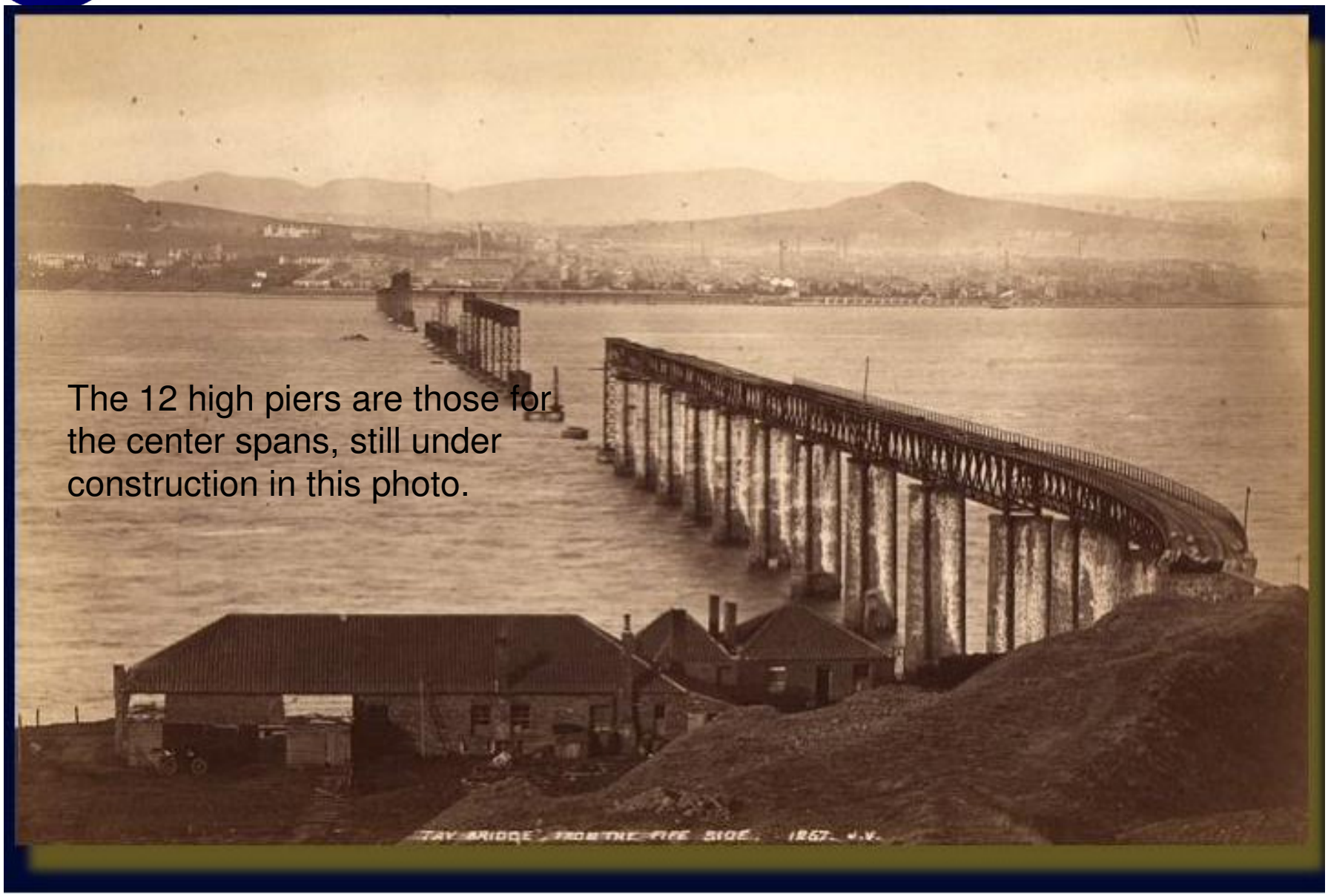
Static Stability, Dynamic Collapse

- *It happened on a dark and windy night…*
  - For our topic, we travel in time, to the world of iron and steam.
  - There we will review a timeless lesson – a lesson for which the presenters have developed tools to put in practice in our world.
- Think back a century and a half –
  - Great Britain, Scotland in particular, a mother country for the industrial revolution and engineering as a profession.
  - A visit to early days of human-rated systems.

The Tay Bridge During Construction



The 12 high piers are those for the center spans, still under construction in this photo.

On the night of December 28th

- The mail train left Edinburgh, Scotland, heading north with 72 passengers for Dundee. The weather turned bad.
- Just before 7 PM, the train slowed to a walk as it approached the newly built bridge over the Firth of Tay, for the signalman to confirm that the way was clear to cross to Dundee.
- At 7 PM, the signalman waved all-clear, and telegraphed ahead to Dundee that the train had cleared his station.

...but never arrived.

- The station in Dundee got the signal that the train had started north over the bridge. It never arrived.
- Dundee tried to telegraph the signalman on the south end of the bridge, and found the circuit was broken.
- Dawn light showed that all 12 of the high bridge piers for the main spans of the bridge, along with the high girder spans they carried and the train, had vanished into the firth.
- Everyone on board had perished.
- An official enquiry followed.

REPORT OF THE COURT OF INQUIRY,

AND

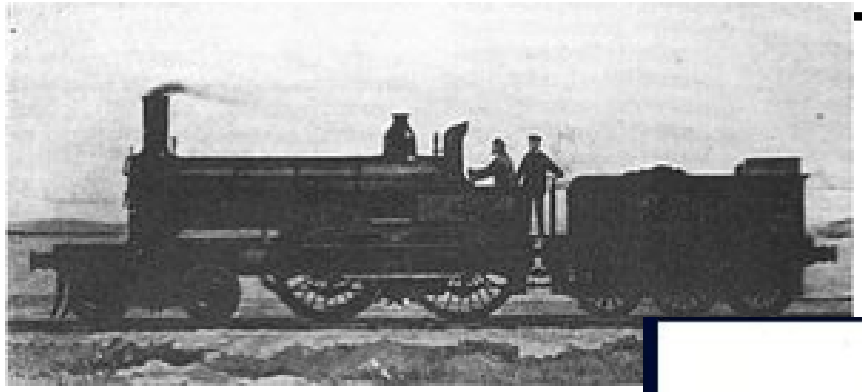
REPORT OF MR. ROTHERY,

UPON THE

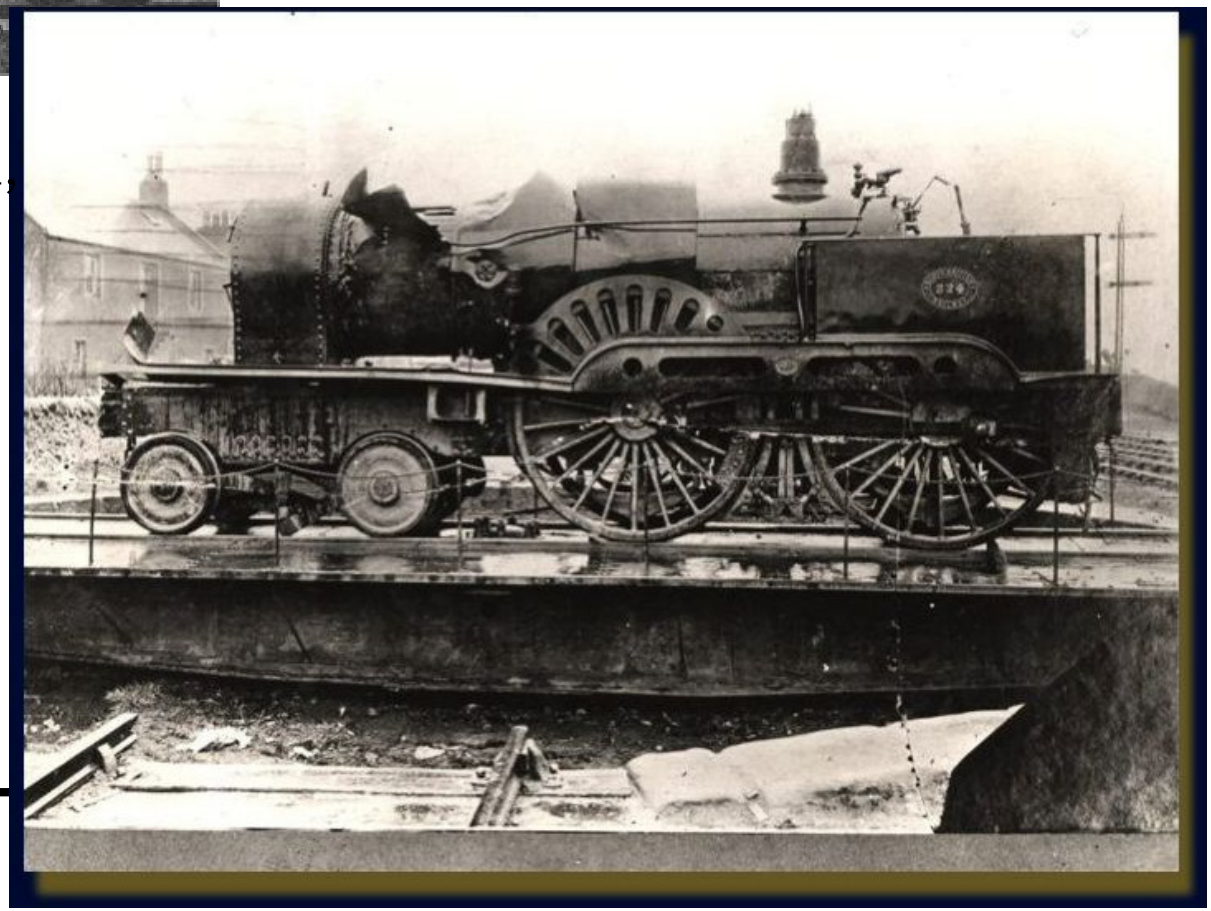
Circumstances attending the Fall of a Portion of the Tay Bridge on the 28th December 1879.

Presented to both Houses of Parliament by Command of Her Majesty.

The 39 ton *Diver*: Before and After



Recovered, refurbished, put back in service, the engine got a nickname



Sparks in the dark

- A second man had been in the signal house, taking shelter from the storm. While the first signalman was busy with telegraph and logbook, this man had watched the train accelerate out onto the bridge.
- He testified seeing a cascade of bright sparks thrown out by the wheels on the lee side, as the train proceeded out into the storm.
- This shows that the gale, in blowing sideways on the train, was forcing the steel wheel flanges sideways against the inner edge of the rail, which would then transfer the lateral forces on the train to the bridge itself.
- The line of enquiry that followed up on this testimony came to the conclusion: “No evidence that engineers allowed for wind load on train transferred to the bridge.”

Static Approach to Design Verification

Investigation uncovered many defects in **design**, materials, and maintenance, so many indeed that that one modern expert proposes that the bridge would have collapsed that night even with no train.

- The investigation did not raise the question we ask now, whether the design considered dynamic forces generated in the course of a bridge-crossing.

Dynamics were relevant. Consider:

Forces on bridge from a moving train distort the railway *in the location of the train – during the course of a bridge-crossing.*

- Lateral wind pressure on the train was transferred to the rails, bending the railway to leeward. In moving forward, the train must produce a wave in the horizontal plane, a wave which, that night, ran with the train onto the high girders.
- The 39-ton engine is now negotiating an off-nominal curve in the tracks, at 30 mph, exerting centrifugal forces additive to lateral forces from gale-force winds on train and bridge!

Our thesis: Model the dynamics!

A model of system behavior as it performs its intended service should be fundamental to in design verification. We

References

The original source is a report to parliament, a milestone in forensic engineering:

Report of the Court of Inquiry and Report of Mr. Rothery upon the Circumstances attending the Fall of a Portion of the Tay Bridge on the 28thDecember 1878. Presented to the Houses of Parliament by Command of Her Majesty, 1880.

This document is the one whose cover is shown in slide 5 of this presentation. It is available as pdf:

http://www.railwaysarchive.co.uk/documents/BoT_TayInquiry1880.pdf

The report to parliament stated that prior to opening the bridge to traffic: "General Hutchinson was directed [by the authorities] to go down and inspect it. His inspection took place on the 25th, 26th, and 27th February 1878, and on the 5th of March following [that is, 21 months before the disaster] he reported that he should wish, if possible, to have an opportunity of 'observing the effects of 'a high wind when a train of carriages is running over the bridge.'" However, that test was never arranged. The authors therefore recognize General Hutchinson as a pioneering advocate of dynamic verification.

The weight of the engine is found at http://medlibrary.org/medwiki/NBR_224_Class

A good overview of the disaster, with an excellent set of references for further reading, is at :

SEMP, the Suburban Emergency Management Project,

http://www.semp.us/publications/biot_reader.php?BiotID=489

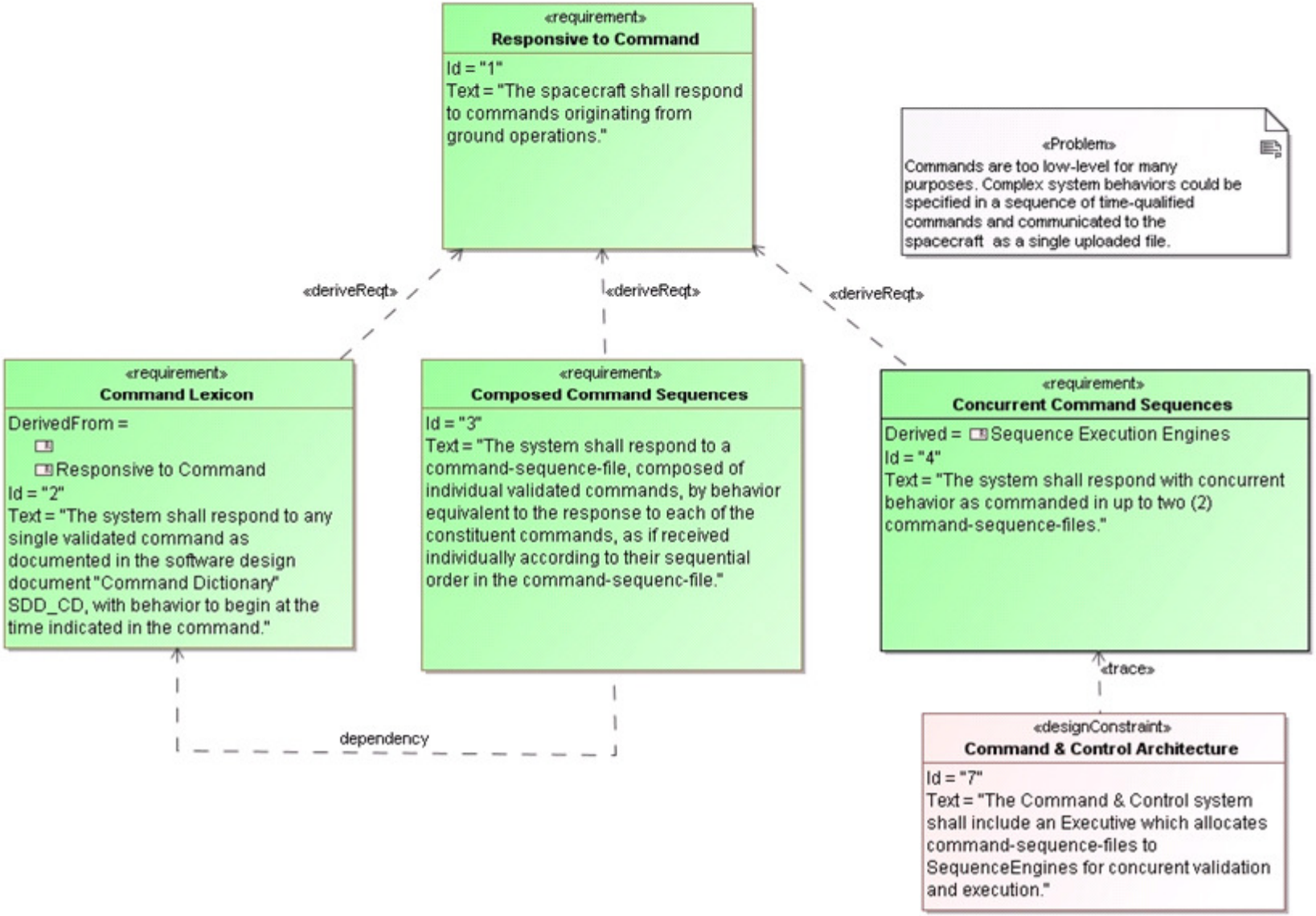
The BBC produced a show in which invited experts researched the event using methods, tools, and science unavailable in 1879. One of these, Dr. Peter Lewis, takes a view similar to that presented here, but also agrees with a consensus view that the fact that 12 high piers collapsed spectacularly indicates that the ironwork had deteriorated and the bridge was unfit for use under any conditions. See:

"What events led up to the disaster", "Forensic Engineering: The Tay Bridge Disaster", BBC: The Open University.

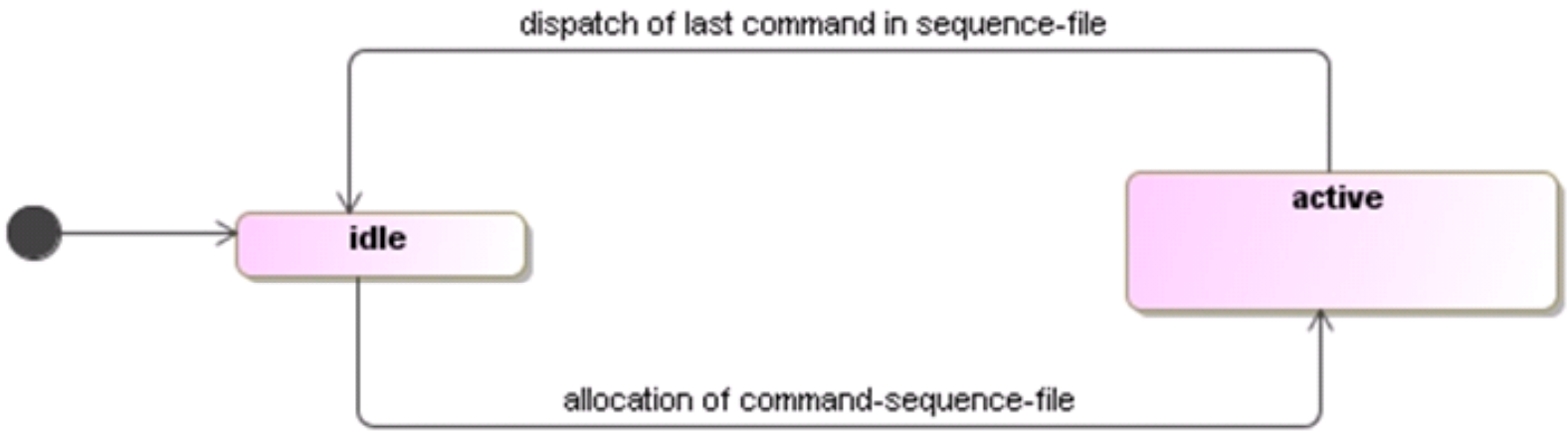
Return to the present day

- To illustrate our dynamic verification tools and approach, a sample space mission project is presented next.
- Starting with requirements shown in a SysML diagram, we follow a number of steps in the elaboration of a design.
- Then show how, by animating the UML model of the behavior of the system as designed, one might find problems which would not be seen in a static view.

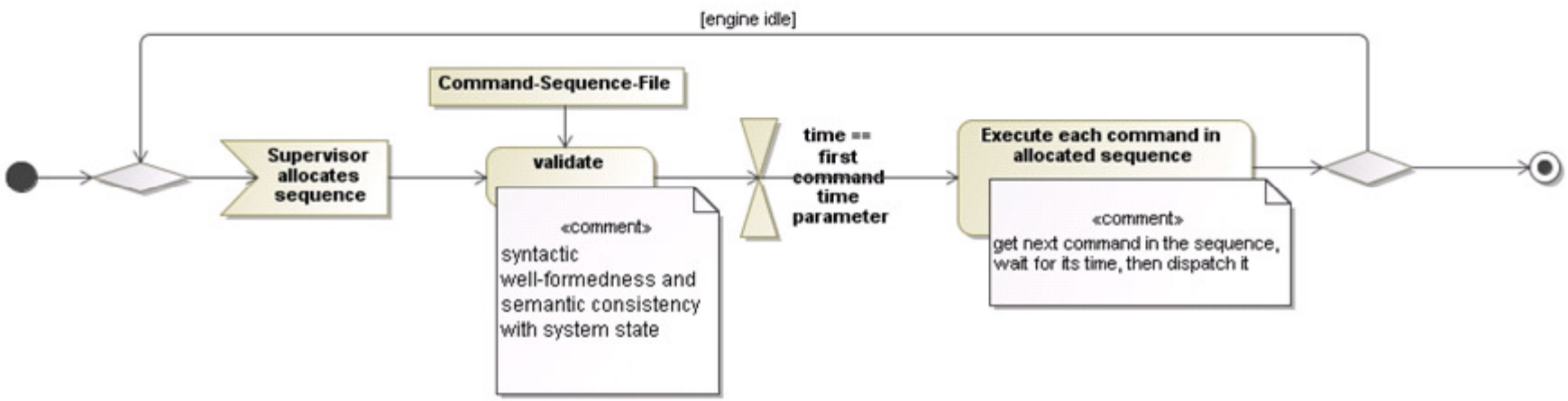
Requirements View



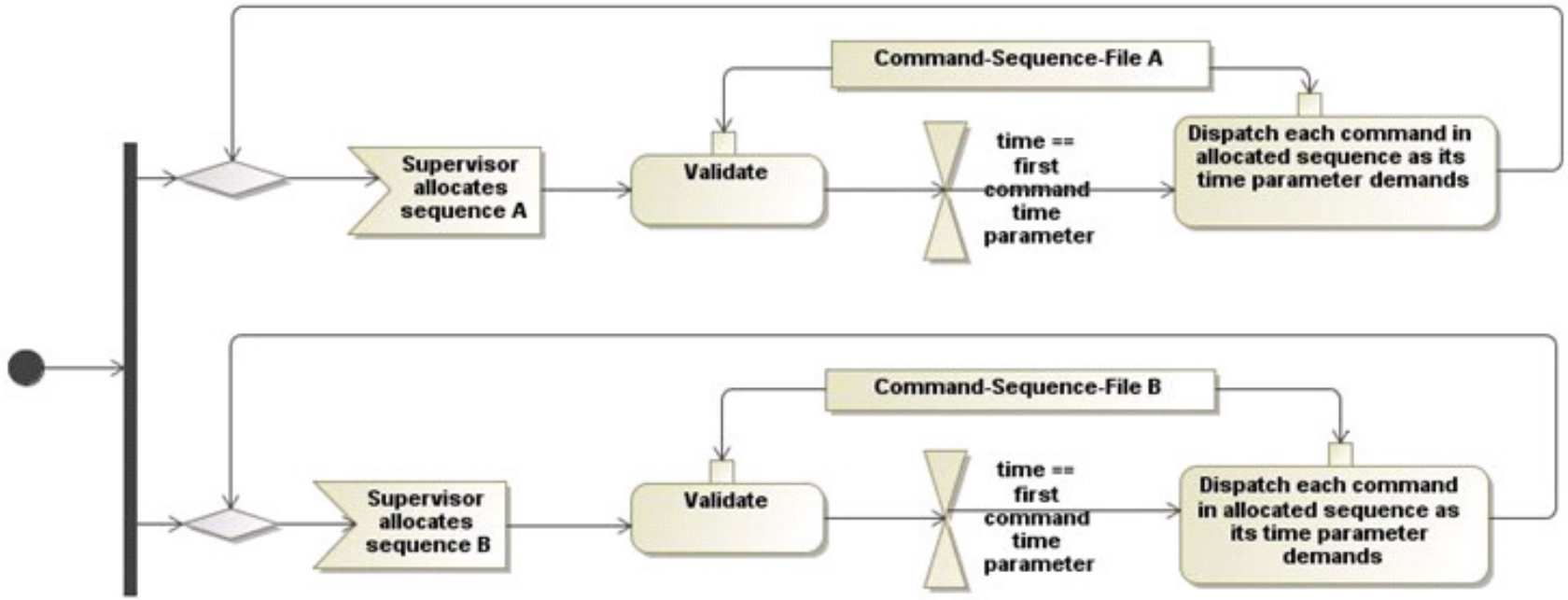
Starting to consider Engine Dynamics



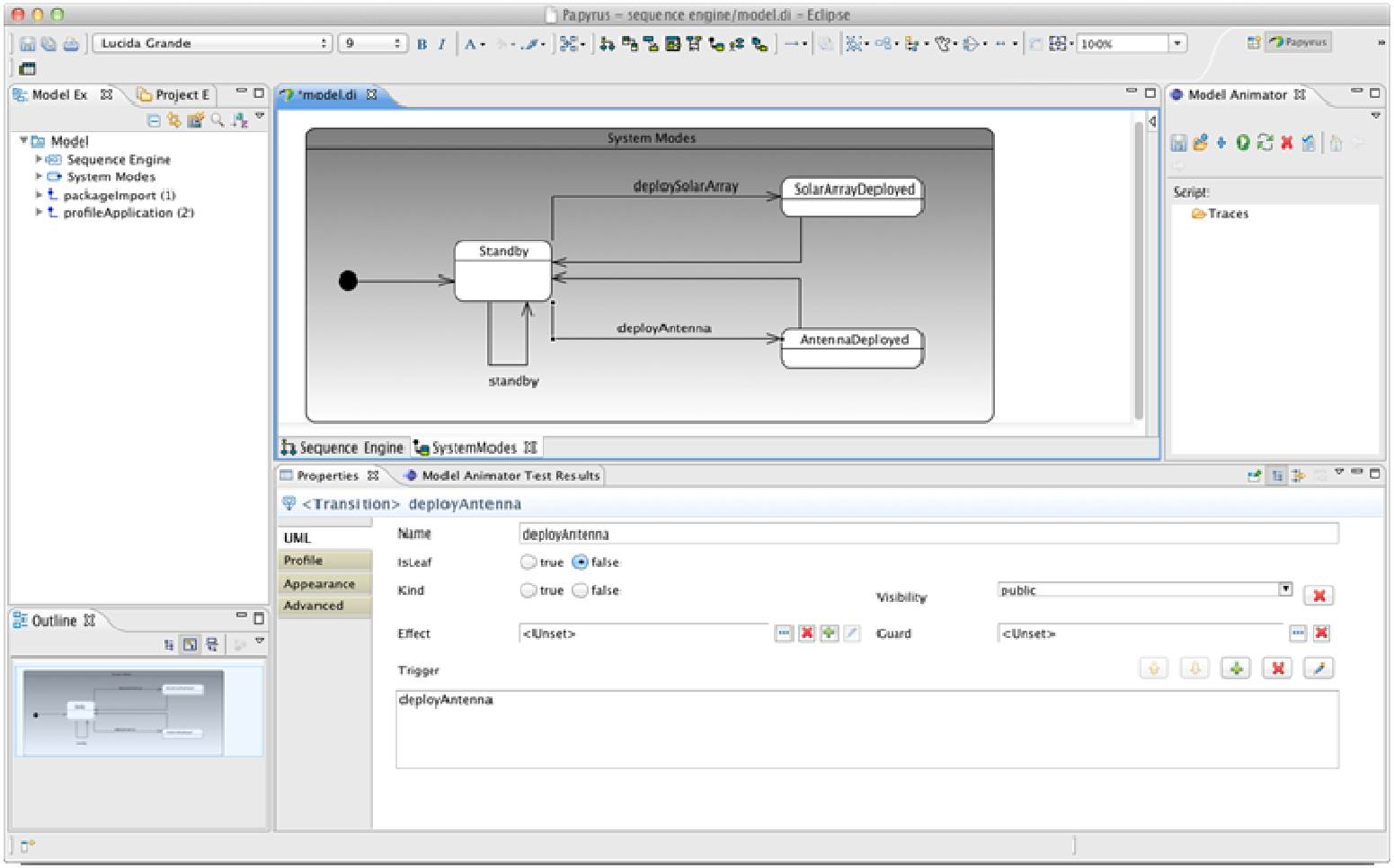
Basic Design for Sequence Engine



Scaling up Behavior for 2 Engines



Model Animator State Machine



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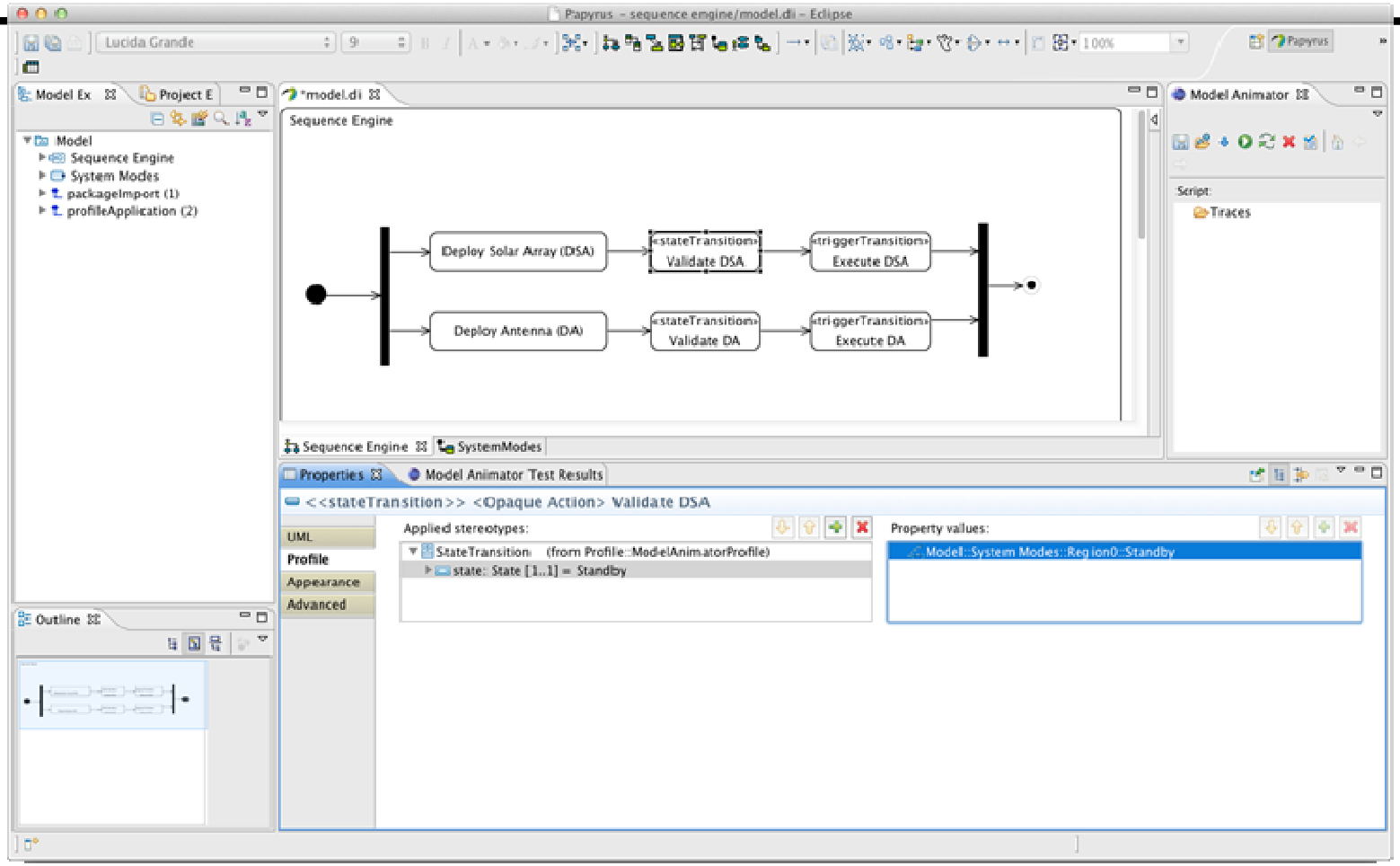
Model Animator – StateTransition



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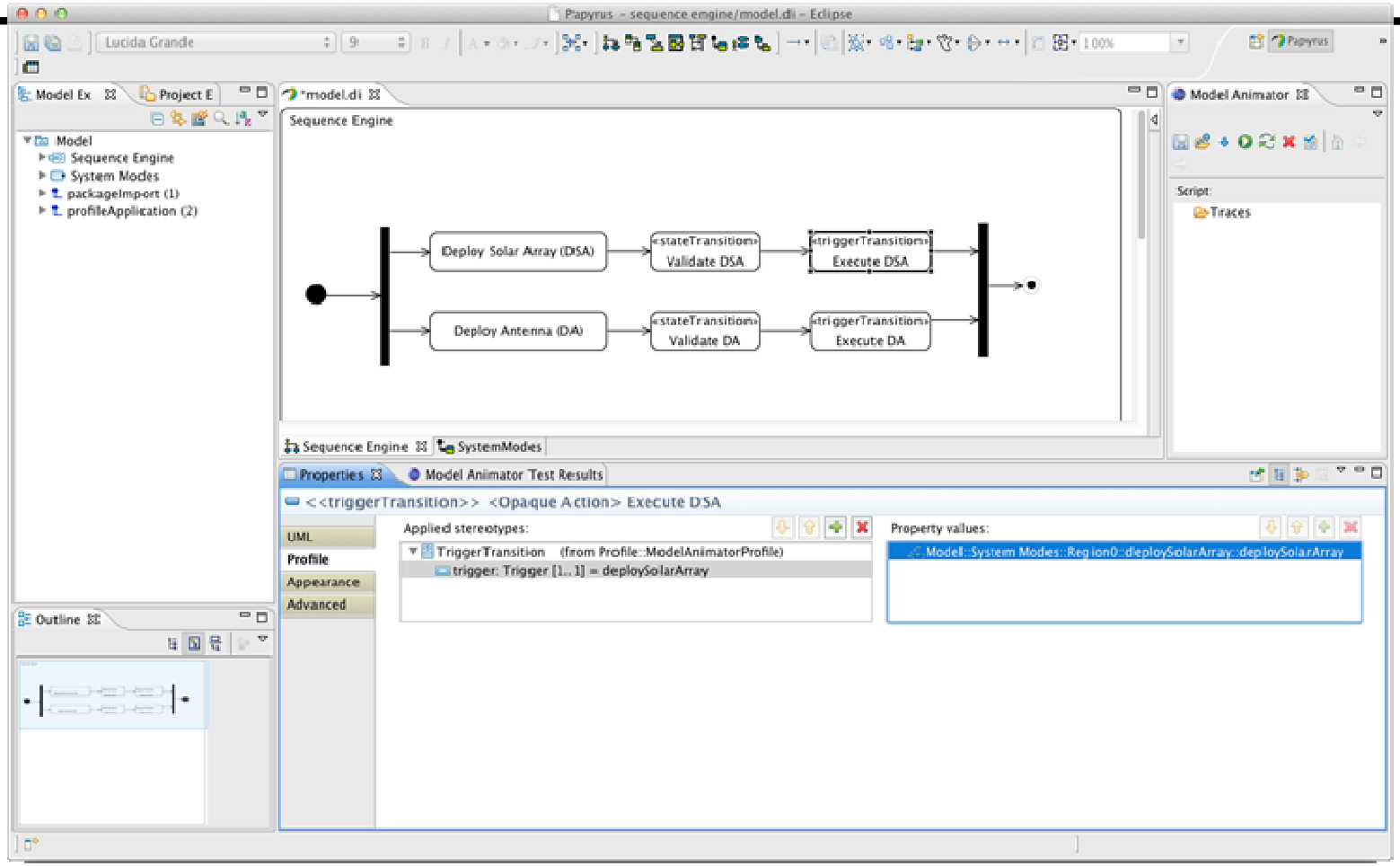
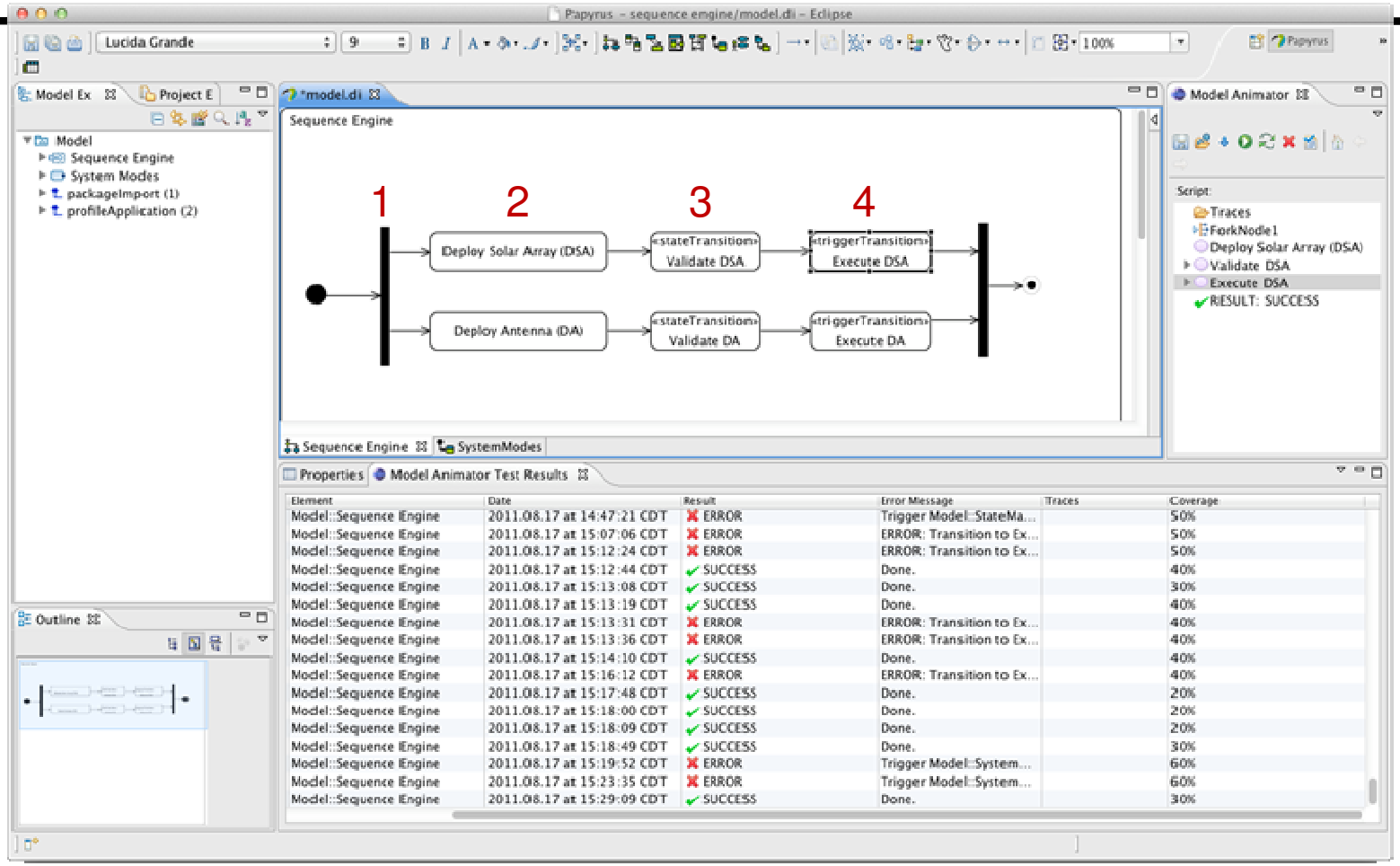
Model Animator – Trigger Transition



Single Engine Success Scenario



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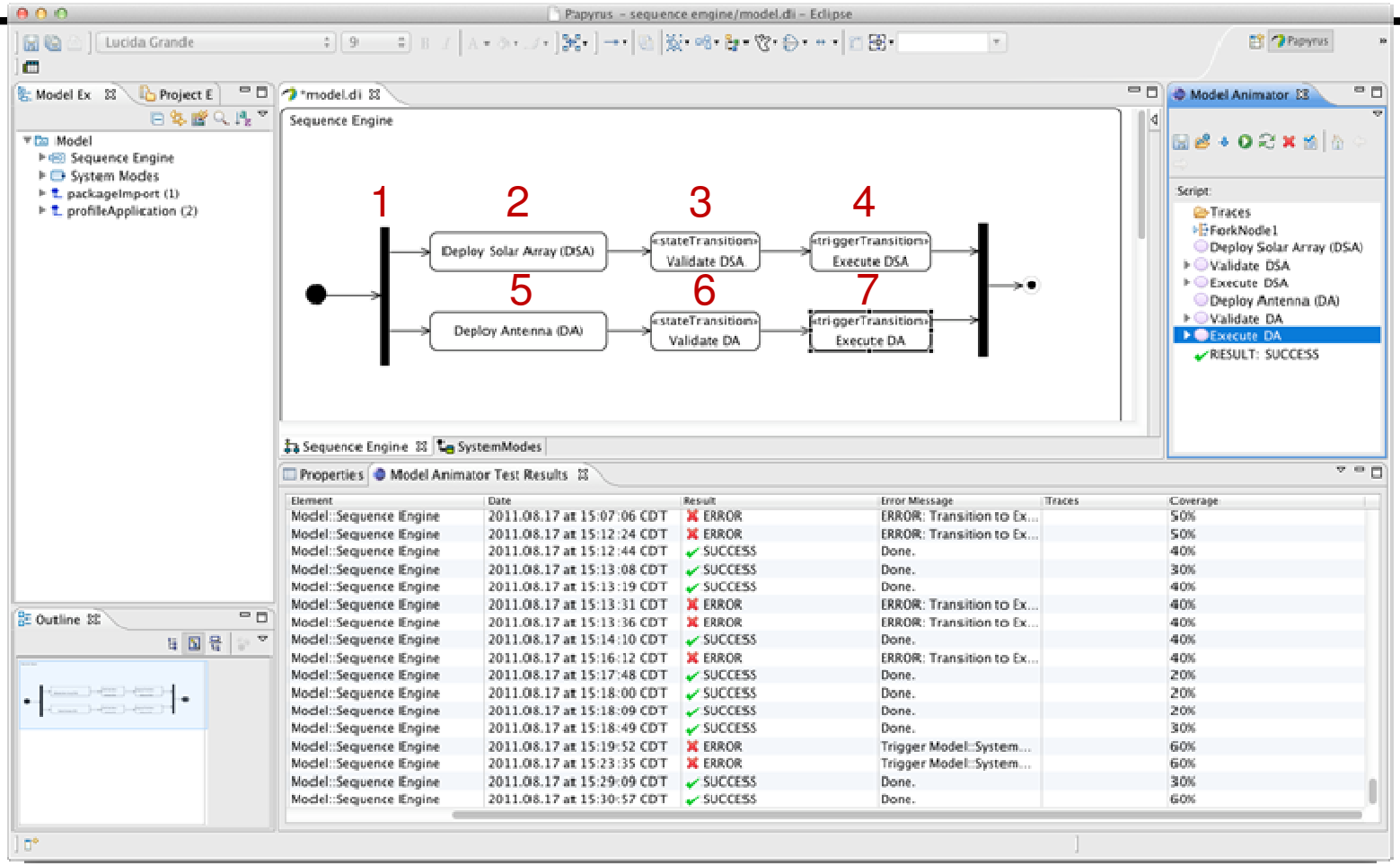
Two Engine Success Scenario (Serial)



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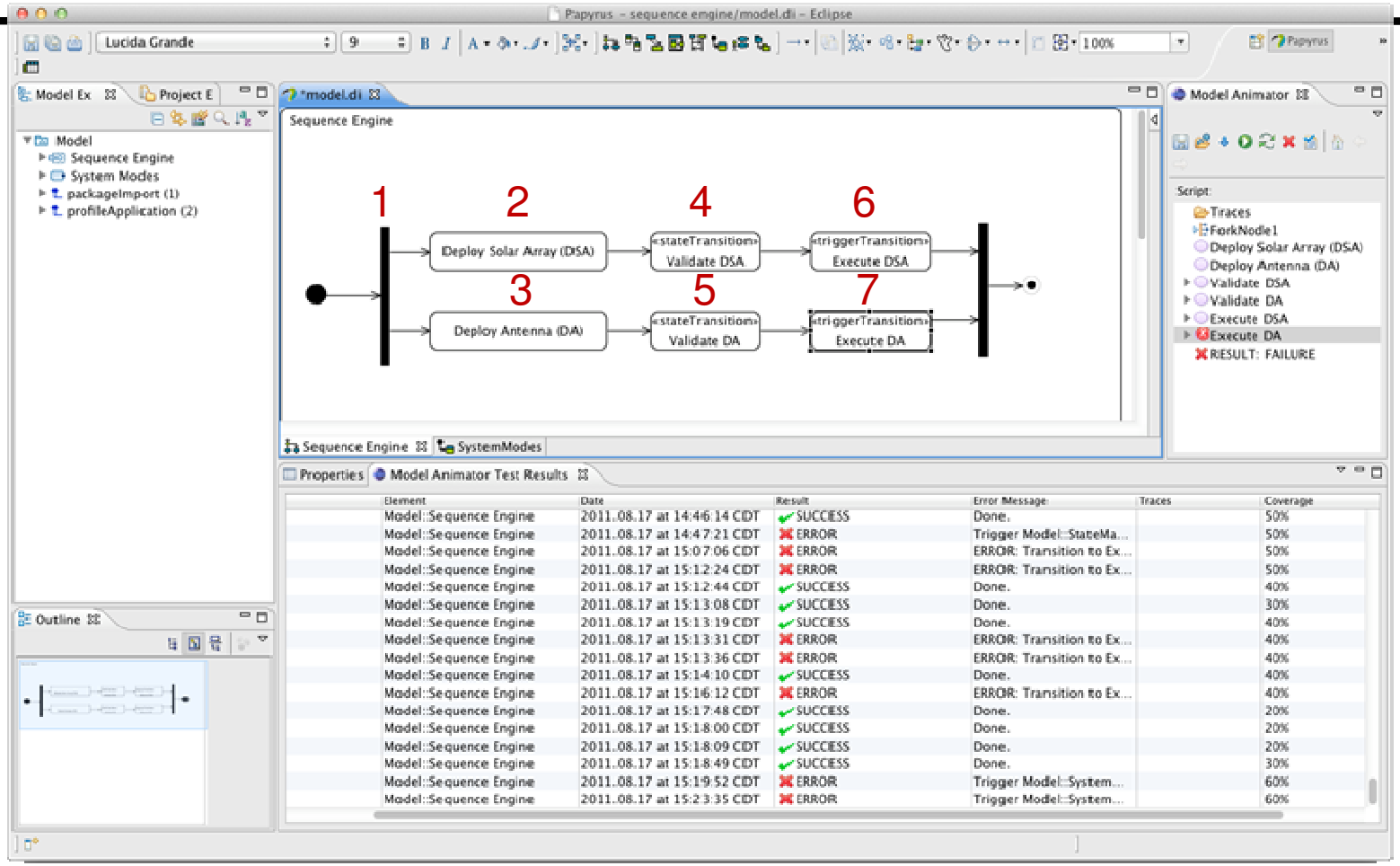
Two Engine Failure Scenario (Interleaved)



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Thank you!