AMERICAN INSTITUTE OF
AERONAUTICS AND ASTRONAUTICS

Formal Verification in Integrated Avionics Systems

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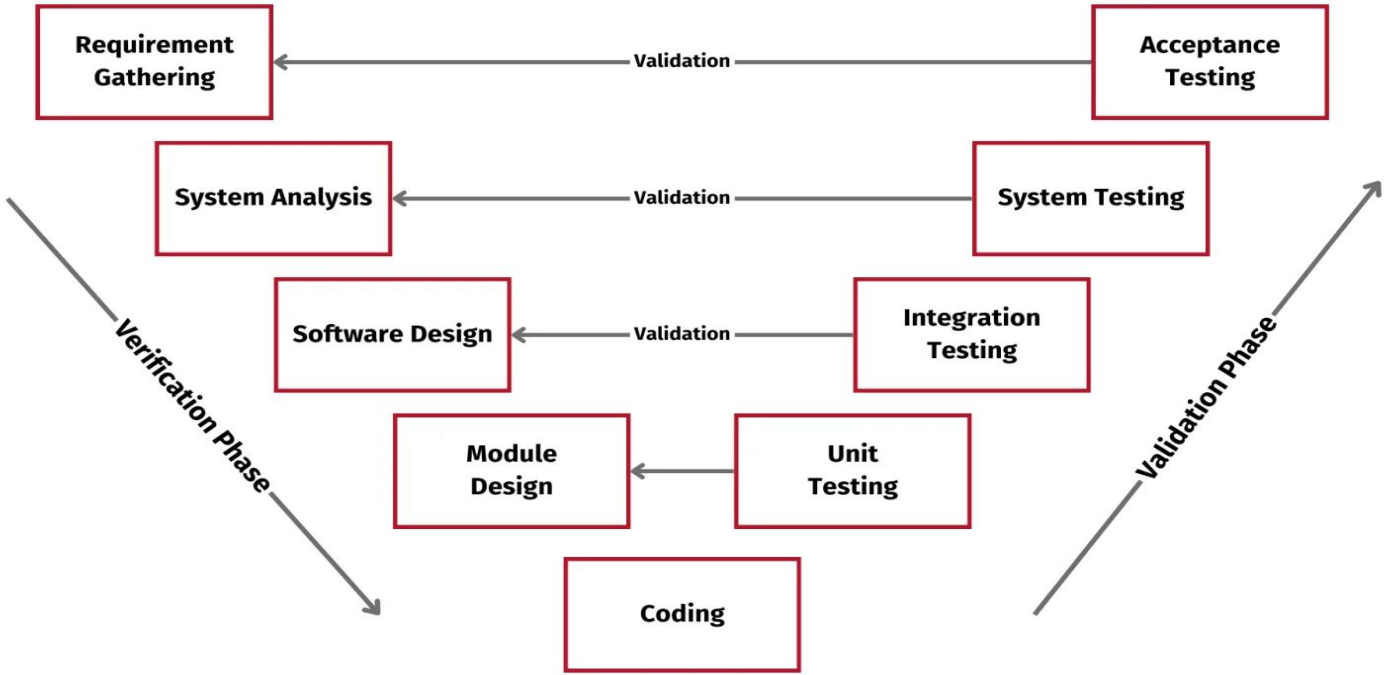
The Evolution of Avionics Architecture

- Modern flight decks are highly integrated software environments, not discrete gauges.
- Advanced and automated navigation systems are a **safety-critical domain** dependent on computational correctness!
- Catastrophic failures largely originate from **errors in the early stages** of the Systems Development Lifecycle (SDLC)

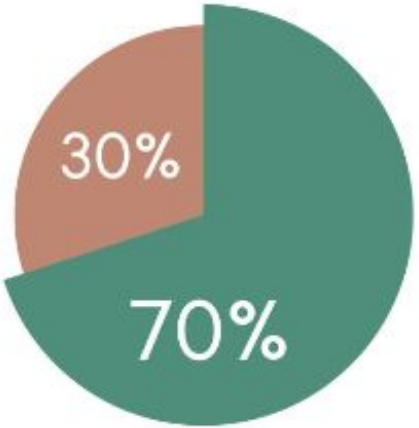
The V-Model Vulnerability

- The aerospace industry traditionally follows the **V-Model** for development.



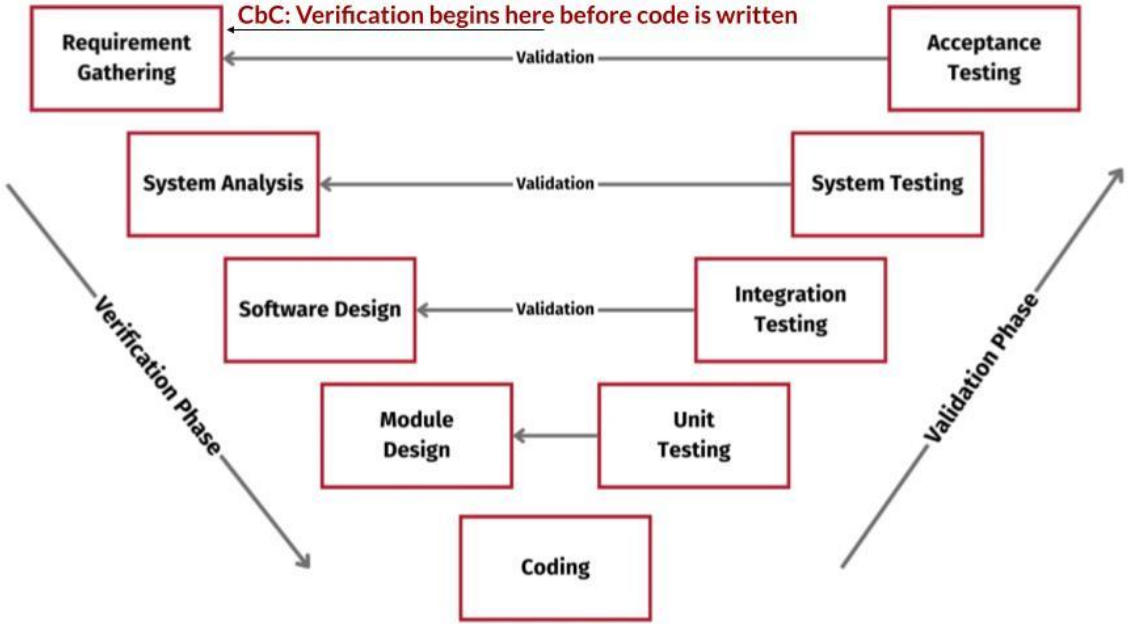
The Economic Burden of V&V

- To meet strict certification standards like **RTCA DO-178C**, developers rely on exhaustive post-implementation testing.
- Dynamic testing only shows some errors, but **never** their absolute absence.
- This reliance on testing to catch upstream errors results in **V&V** activities taking up to **70% of total development.**



Proposed Solution: Correctness by Construction

- We propose a "**Correctness by Construction**" (**CbC**) framework, shifting verification to the left side of the V-Model using **s(CASP)**'s formal specification.



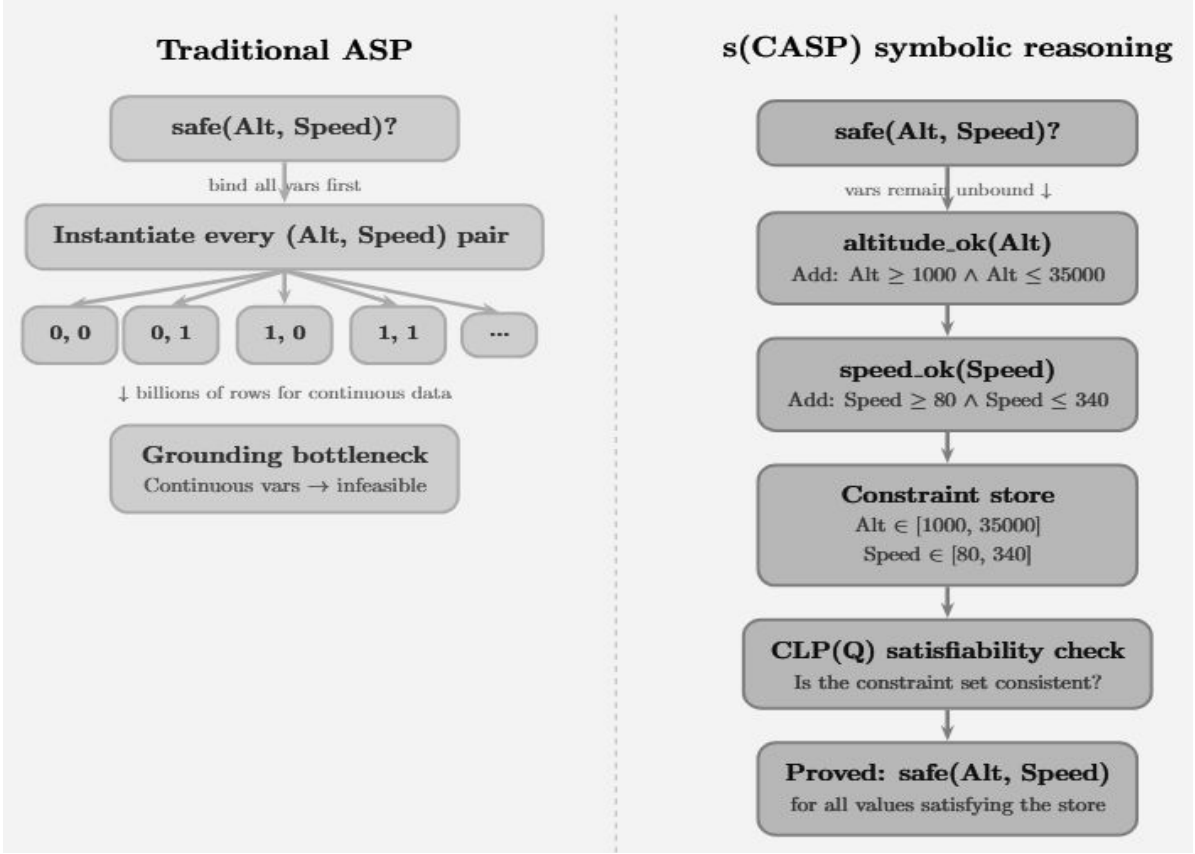
Overcoming the Grounding Bottleneck with s(CASP)

- **The grounding bottleneck**:
  - Traditional formal methods struggle with avionics scale due to the "**grounding bottleneck**", where all variables must be **instantiated before solving**.
  - This is impossible for continuous data like altitude or airspeed.

Overcoming the Grounding Bottleneck with s(CASP)

- Our framework utilizes **s(CASP)**, a goal-directed **Answer Set Programming** system that **avoids grounding** entirely.
- Using **top-down, query-driven execution** it keeps variables symbolic and accumulates constraints, mathematically bounding conditions where safety requirements might fail across the entire continuous flight data.

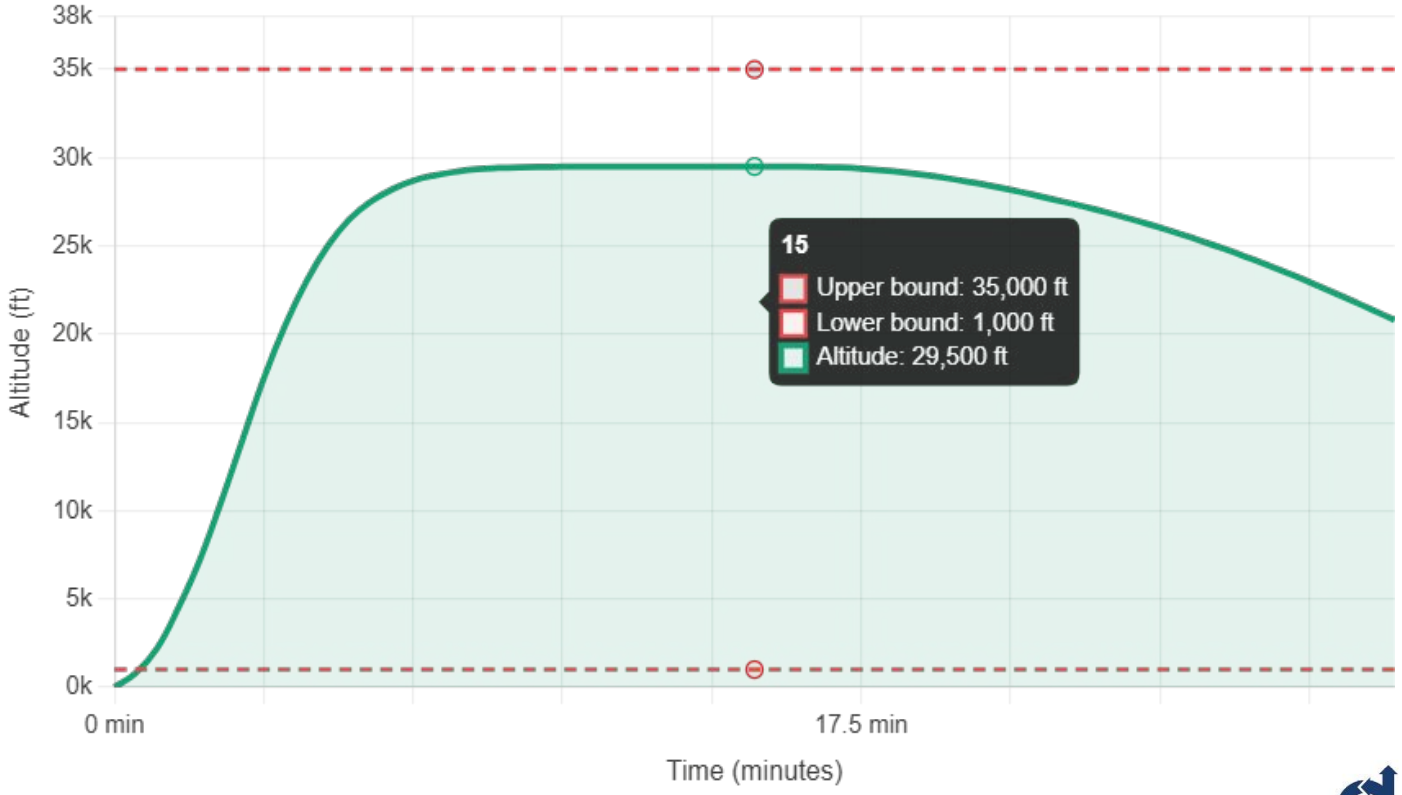
ASP vs s(CASP) Diagram



Continuous Verification via CLP(Q)

- Avionics systems interact with the physical world over **continuous** time and space.
- Our framework integrates Constraint Logic Programming over rational numbers (**CLP(Q)**).
  - **CLP(Q)** represents rational numbers exactly, not floating-point approximations.
  - Formally verifies requirements over complex flight equations and inequalities.
  - Ensures operational integrity across an infinite state space.

Sample Flight Altitude Profile



Automating the Traceability Matrix (RTM)

- Maintaining a Requirements Traceability Matrix is traditionally a manual, error-prone process.
- Our framework automates this by utilizing **s(CASP)** justification trees.
  - When a property is verified, the system generates a **structural logical path** for the conclusion.
  - By mapping symbolic logic to human-readable text via the **#pred** directive, it produces a mathematically proven, human-readable **RTM** that satisfies certification authorities.

Automated RTM via s(CASP) Justification Trees

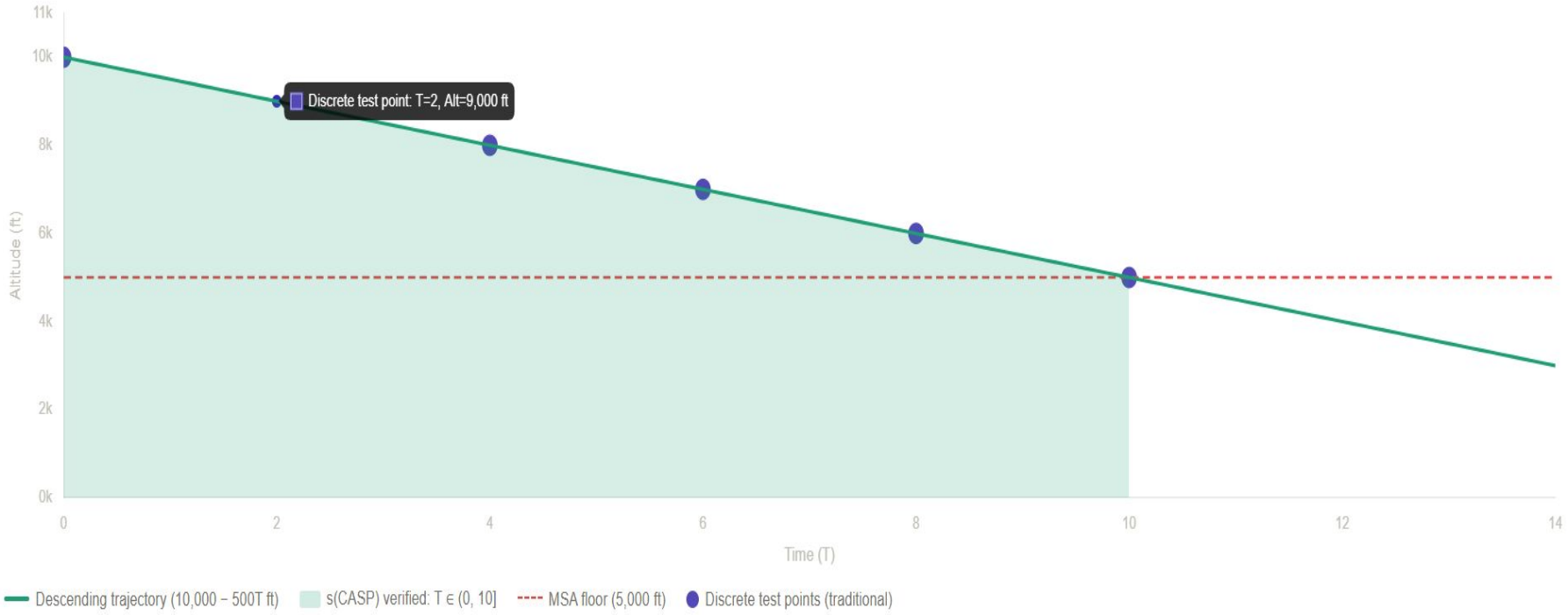
Requirement Human-readable	s(CASP) query Symbolic logic	Justification tree Logical path	#pred output RTM entry
Altitude bounds Alt ∈ [1000, 35000 ft]	`safe(Alt,_)` `altitude_ok(Alt)`	safe ← alt_ok ← constraint held	Verified Altitude is safe
Airspeed limits Speed ∈ [80, 340 kn]	`safe(_,Speed)` `speed_ok(Speed)`	safe ← spd_ok ← constraint held	Verified Speed is safe
Trajectory safety Continuous path valid	`safe_path(T)` `clp_check(T)`	path ← clp_ok ← bounds satisfied	Verified Path is safe
IMA partitioning Resource isolation	`isolated(A,B)` `no_conflict(A,B)`	isolated ← no_conf ← partition held	Verified Apps isolated

RTM auto-generated via #pred directive — symbolic logic mapped to human-readable certification evidence

Case Study: Trajectory Safety Verification

- In a traditional V-Model, engineers test discrete points (altitudes at specific times), leaving space between points unverified.
- We applied the framework to the Minimum Safe Altitude (**MSA**) monitoring function.
  - Using **s(CASP)** and **CLP(Q)**, we queried the system to find the exact mathematical bounds of the safe operation.
  - The result proved the trajectory safe for any continuous time within a specific range.
  - Eliminates the risk of latent errors between discrete test cases.

MSA Flight Trajectory Graph



Automated RTM with MSA Trajectory

DO-178C Requirement	s(CASP) predicate #pred directive	Justification tree Logical path to conclusion	Auto-generated Human-readable RTM entry

Trajectory safety
MSA monitoring function must be safe for all T in operating range
	`safe_trajectory (T1, T2)`
	Query issued:
	`?- safe_trajectory (0, T).`
		safe_trajectory(0,T)
		← altitude_at(T, A)
		← T ≥ 0
		← A = 10000−500·T
		← terrain_clearance(A)
			The flight trajectory is safe between time 0 and T, with T > 0 and T ≤ 10
			Model: T ∈ (0, 10]

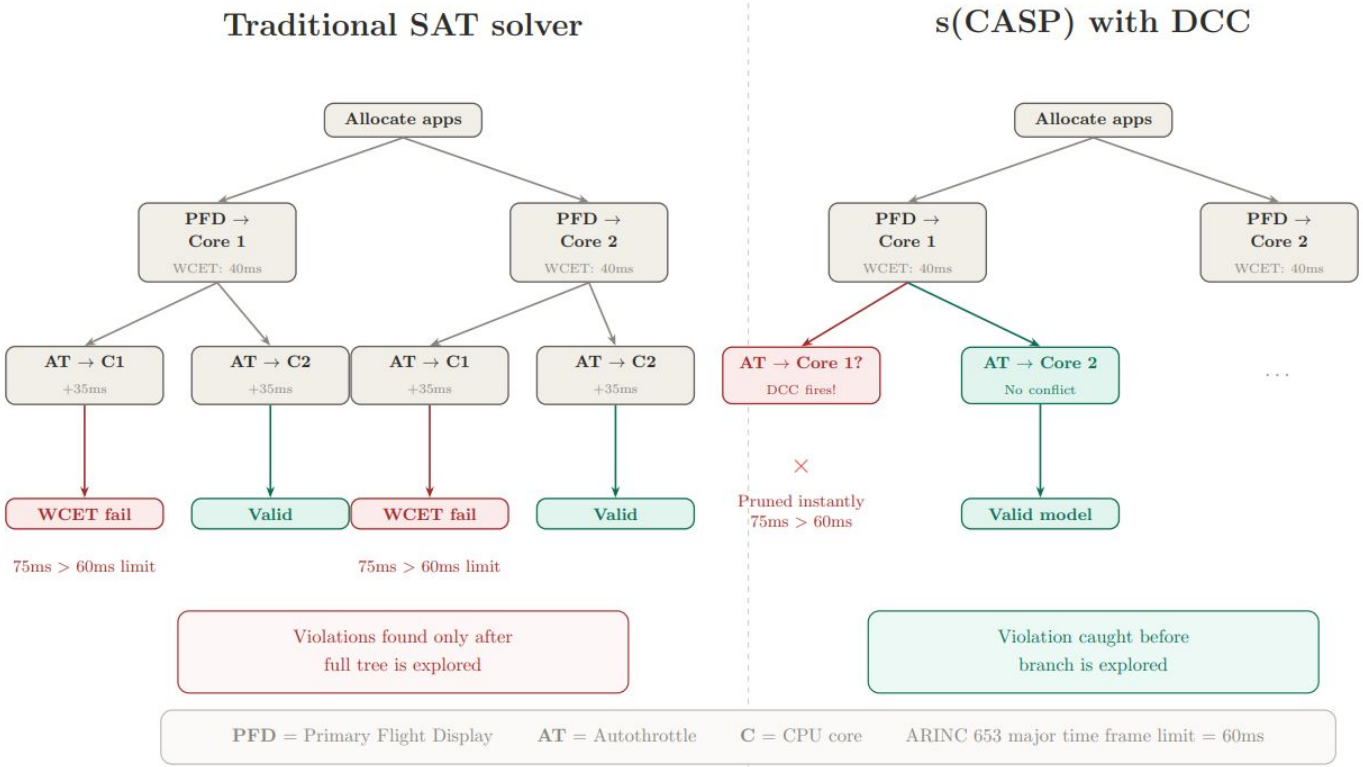
Altitude model Aircraft descends at 500 ft/unit from 10,000 ft initial alt.	`altitude_at(T, A)` T #>= 0 Initial_A #= 10000 A #= 10000−500·T	altitude_at(T, A) ← T ≥ 0 [CLP(Q)] ← A = 10000−500·T ← constraint satisfied	The aircraft altitude at time T is A, where T ≥ 0 and A = 10000 − 500·T
Terrain clearance Altitude must stay at or above MSA of 5,000 ft	`terrain_clearance(A)` MinSafeAlt #= 5000 A #>= MinSafeAlt	terrain_clearance(A) ← A ≥ 5000 [CLP(Q)] ← global constraint holds	The altitude A maintains safe terrain clearance, because A ≥ 5000

Generated by: s(CASP) --tree --human flags | #pred directives map symbolic logic to DO-178C certification evidence
Result: safe_trajectory(0, T) proved for all T ∈ (0, 10]

Scalability in Integrated Modular Avionics (IMA)

- In modern **IMA** environments, multiple applications share resources, causing combinatorial complexity and "*state-space explosion*" during verification.
- Our framework addresses this through Dynamic Consistency Checking (**DCC**).
  - **DCC** interleaves model generation with consistency checking, instantly **pruning** execution branches that violate global safety constraints (such as CPU overruns).
  - It allows formal verification of complex, multi-partition architectures without timeouts, unlike traditional solvers.

DCC: Full Tree Exploration vs. Early Pruning



Conclusion and Future Work

- The complexity of modern avionics has pushed the traditional model to its economic and technical **limits**.
- A "*Correctness by Construction*" model is now **necessary** to ensure safety.
- Our framework automates traceability, prunes complex search spaces, and verifies continuous flight logic.
- **Future work** involves integrating this into Model-Based Systems Engineering (MBSE) toolchains and extending the methodology to autonomous UAVs and Advanced Air Mobility platforms.

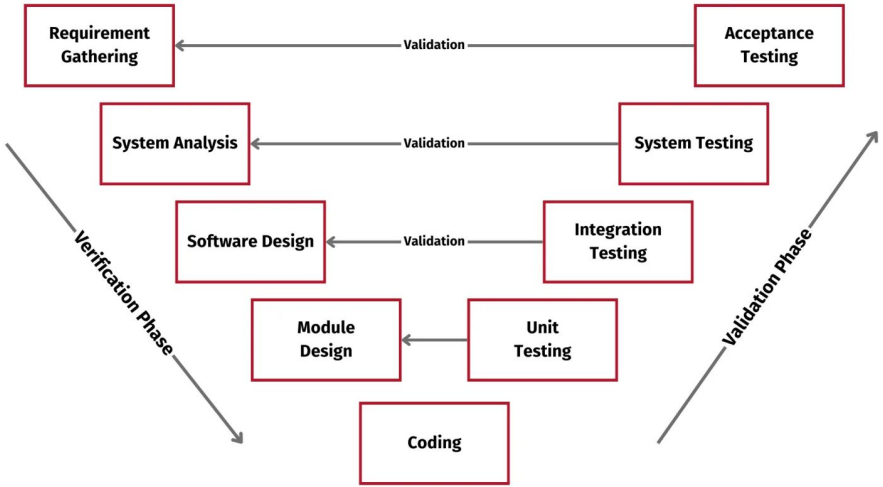
AEROSCASP

Questions?

The following slides were not included in the final presentation.

The V-Model Vulnerability

- The aerospace industry traditionally follows the **V-Model** for development.
- **A major flaw** is ambiguities and logical inconsistencies from Requirements Analysis often remain through design and implementation.
- **Defects** are typically only discovered in **late-stage** Verification and Validation (**V&V**).
- The cost of remediation increases exponentially as the project progresses, creating a "*latent error*" trap.

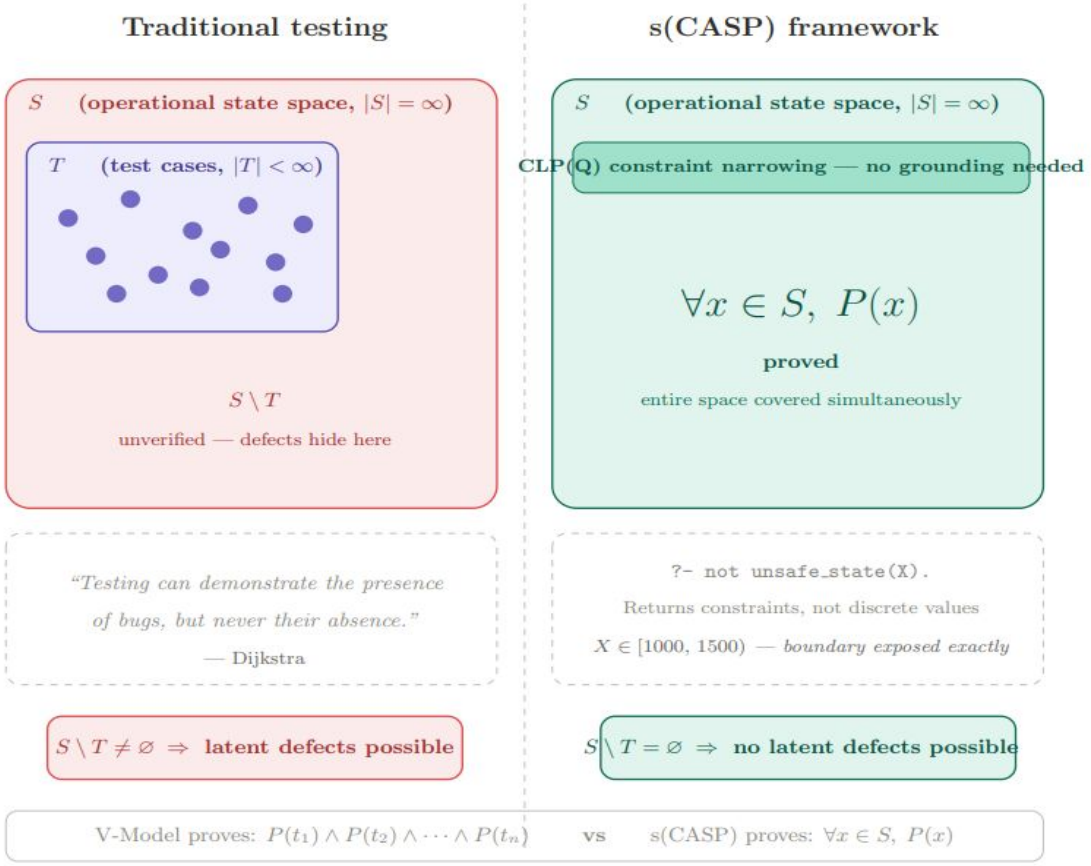


Epistemological Limits vs. Mathematical Certainty

- Traditional testing is limited because the operational state space of an aircraft is infinite, while the number of test cases is always finite.
- Testing can only verify a subset of states, leaving an infinite set of states unverified.

- Our **s(CASP)** framework uses universal quantification to evaluate continuous intervals.
  - Shifting from sampling points to proving properties over the entire state space provides a structural guarantee of safety that traditional testing cannot match.

Testing Methodologies



Proposed Solution: Correctness by Construction

- We propose a "*Correctness by Construction*" (**CbC**) framework.
  - Shift verification process to "*left side*" of the V-Model.
  - **s(CASP)**'s Formal specification establishes a rigorous mathematical groundwork for system properties before code is written.
  - Move burden of proof from post-facto testing to a priori mathematical verification.
  - Provable guarantee that software is semantically consistent with safety requirements.

Limitations and Current Scope

s(CASP) predicates are currently written manually by a verification engineer with formal logic expertise. The translation from natural language requirements is not yet automated." This framework is a proof-of-concept. The case studies use synthetic data, not live flight software from a certified avionics program. Formalizing continuous flight dynamics in CLP(Q) requires domain expertise in both aerospace engineering and constraint logic programming, which limits near-term accessibility.

The Evolution of Avionics Architecture

- Modern flight decks have transitioned from federated, discrete gauges to highly integrated software environments.
- Advanced and automated navigation systems create a **safety-critical domain** where operational integrity depends on computational correctness.
- Catastrophic failures largely originate from **errors in the early stages** of the Systems Development Lifecycle (SDLC), rarely by low-level hardware faults.

The V-Model Vulnerability

- The aerospace industry traditionally follows the V-Model for development.
- **A major flaw** is ambiguities and logical inconsistencies from the Requirements Analysis phase (**Phase Two**) often remain latent through design and implementation.
- These defects are typically only discovered during the **late-stage** Verification and Validation (**V&V**) phases.
- The cost of remediation increases exponentially as the project progresses, creating a "*latent error*" trap.

The Economic Burden of V&V

- To meet strict certification standards like **RTCA DO-178C**, developers rely on exhaustive post-implementation testing.
- Dynamic testing can only demonstrate the presence of errors, but **never** their absolute absence.
- This reliance on testing to catch upstream errors results in **V&V** activities taking up to **70% of total development.**
- This prohibitive cost stifles innovation and delays the deployment of next-generation avionics systems.

Overcoming the Grounding Bottleneck with s(CASP)

- Traditional formal methods often struggle with the scale of avionics due to the "*grounding bottleneck*," where all variables must be instantiated before solving.
  - Impossible for continuous data like altitude or airspeed.
- Our framework utilizes **s(CASP)**, a goal-directed Answer Set Programming system that avoids grounding.
  - It models complex, continuous flight dynamics by using top-down, query-driven execution to mathematically bound the conditions where safety requirements might fail.

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