Scaling Up Formal Verification

Dionisio de Niz, Ph.D.

Principal Researcher & Technical Director
Assuring Cyber Physical Systems Directorate

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Formal Verification of Complex Software

Formal Verification Does not Scale

Hence: Minimize what must be verified

Prevent Unverified Software to Behave Unsafe

- Enforcer: Detect & Correct Unsafe Behavior
- Verify Enforcer

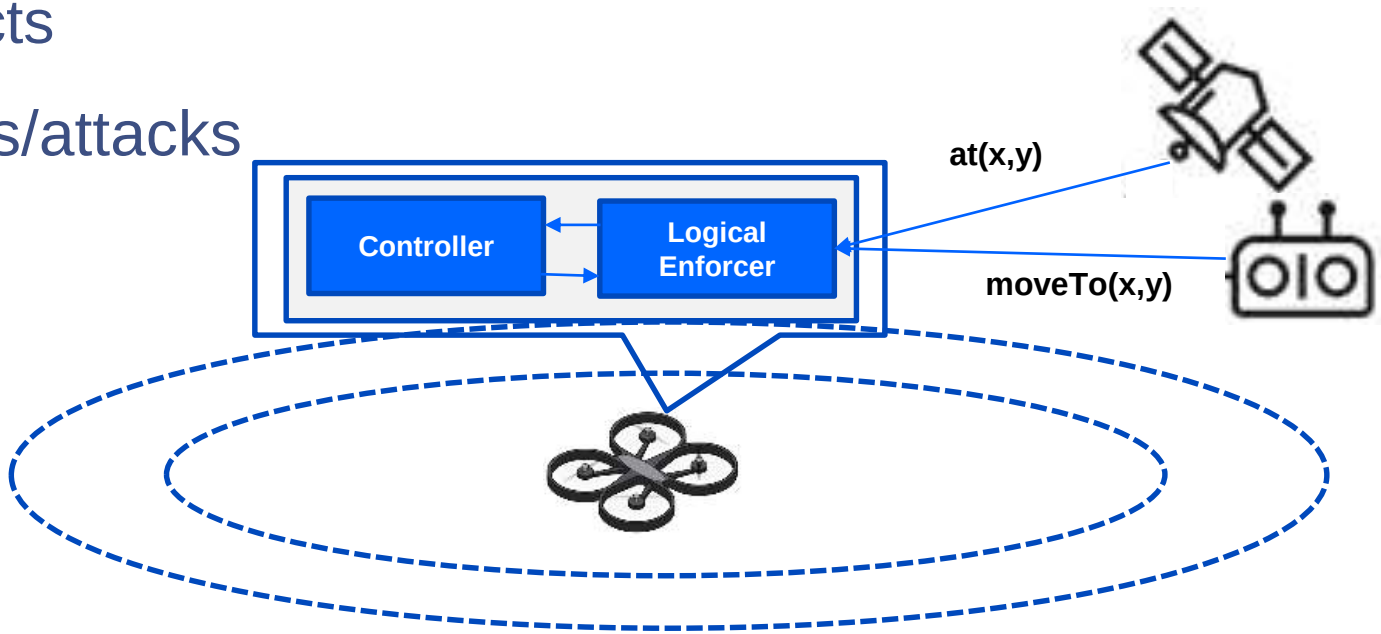
Enforcement-based Verification

Add **simpler (verifiable)** runtime enforcer to make algorithms predictable

Formally: specify, verify, and compose multiple enforcers

- Logic: Enforcer **intercepts/replaces** unsafe action
- Timing: at **right time**
- Physics: verified physical effects

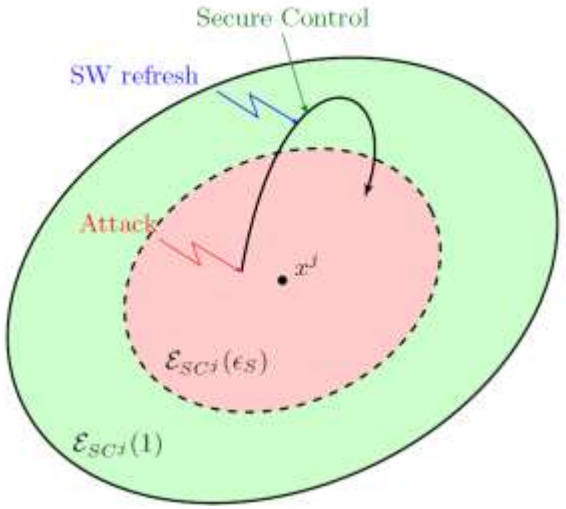
Protect enforcers against failures/attacks



Verifying Physics (Control Theory)

Recoverable Set: $\varepsilon_{SCj}(1)$

Safety Set: $\varepsilon_{SCj}(\epsilon_s) \triangleq \epsilon_s\, \varepsilon_{SCj}(1)$



Controlled System: $\dot{x} = f_\varphi(x) \triangleq f(x, \varphi(x))$

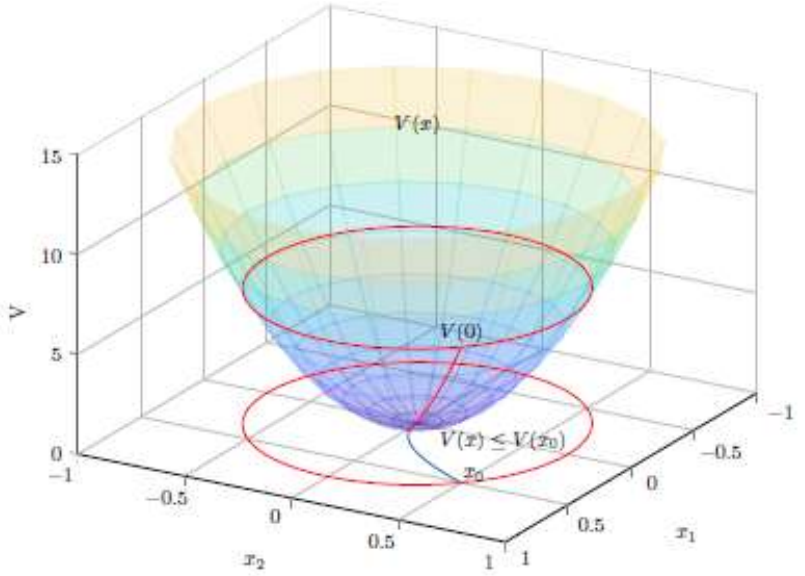
Lyapunov Function: $V_\varphi : \mathbb{R}^n \to \mathbb{R}$, $\mathcal{N}_{V_\varphi}(x_{eq}) \subseteq \mathcal{N}_\varphi(x_{eq})$,

$V_\phi(x_{eq}) = 0$ and $\forall x \in \mathcal{N}_{V_\varphi}(x_{eq}) - \{x_{eq}\}$: (i) $V_\varphi(x) > 0$,

$$\dot{V}_\varphi(x) = \frac{\partial V}{\partial x} \cdot f_\varphi(x) < 0$$

Lyapunov level set:For $\epsilon > 0$,

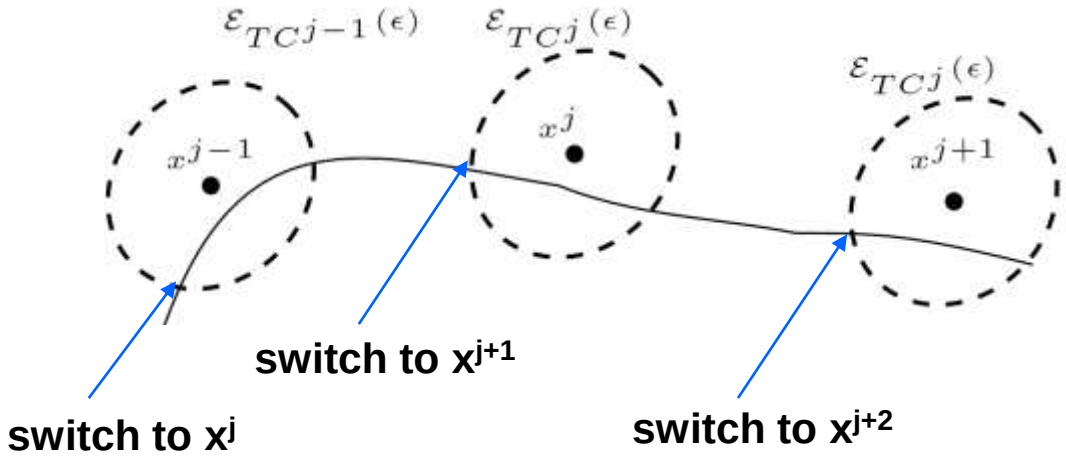
$$\mathcal{E}_\varphi(\epsilon) = \{x \in \mathcal{N}_{V_\varphi}(x_{eq}) | V_\varphi(x) \leq \epsilon\}. \qquad \epsilon \leq 1$$



Analysis of Mission Progress

Idea:

Provide a sequence of waypoints that represent a sequence of equilibrium points around which we define the Safe Set.



Goal:

- Safety transition from one waypoint to the next one.
- Liveness (in the case of no errors)

Analysis of Mission Progress Enforcing Unsafe Behavior

6 DOF ⇒ 12 state variables

$$\ddot{p}_x = -\cos\phi \sin\theta \frac{F}{m}$$

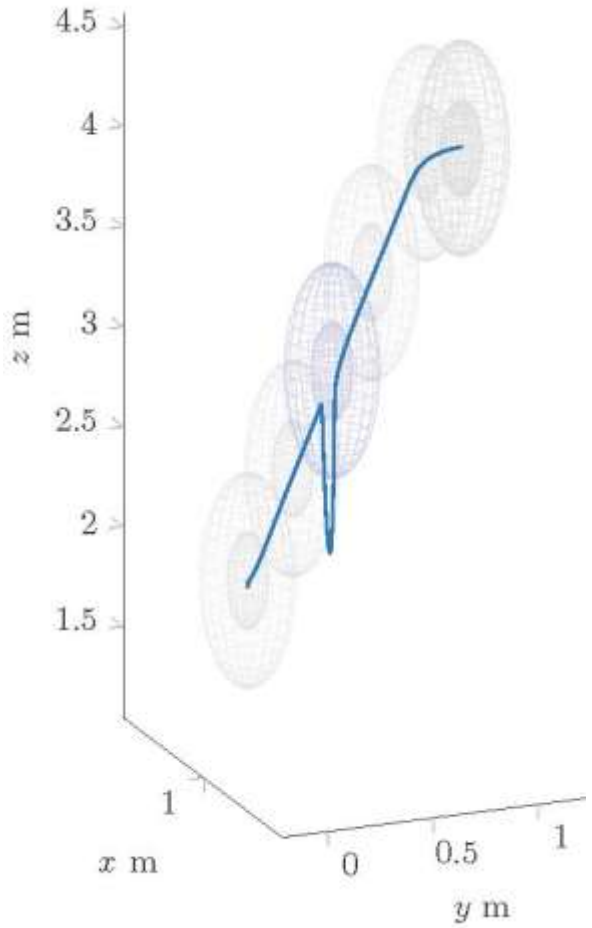
$$\ddot{p}_y = \sin\phi \frac{F}{m}$$

$$\ddot{p}_z = g - \cos\phi\cos\theta \frac{F}{m}$$

$$\ddot{\phi} = \frac{1}{J_x}\tau_\phi$$

$$\ddot{\theta} = \frac{1}{J_y}\tau_\theta$$

$$\ddot{\psi} = \frac{1}{J_z}\tau_\psi.$$



Linear design:

- **linearize at equilibrium**
- **assume full state available**
- **LQ state feedback design**
- **reference points = equilibrium states**

Drone Experiment

Are We Done Yet?

Scalable Verification

- Only verify safety-critical components
- Guarding unverified one

Trust

- Protect verified components
- Against attacks or bugs from unverified components

Enforcing Unverified Components

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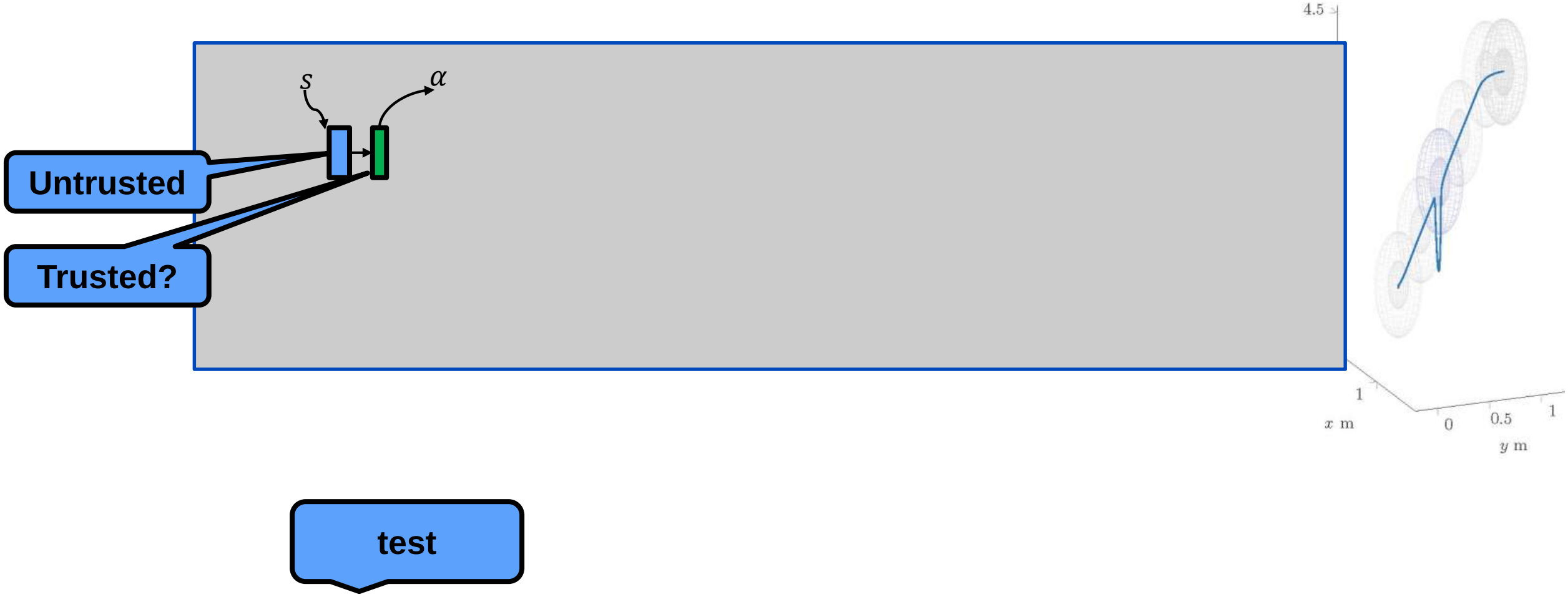
Enforcing Unverified Components



But enforcer can be corrupted (bug or cyber attack)

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Add Memory Protection

Trusted = Verified & Protected

Are We Done Yet?

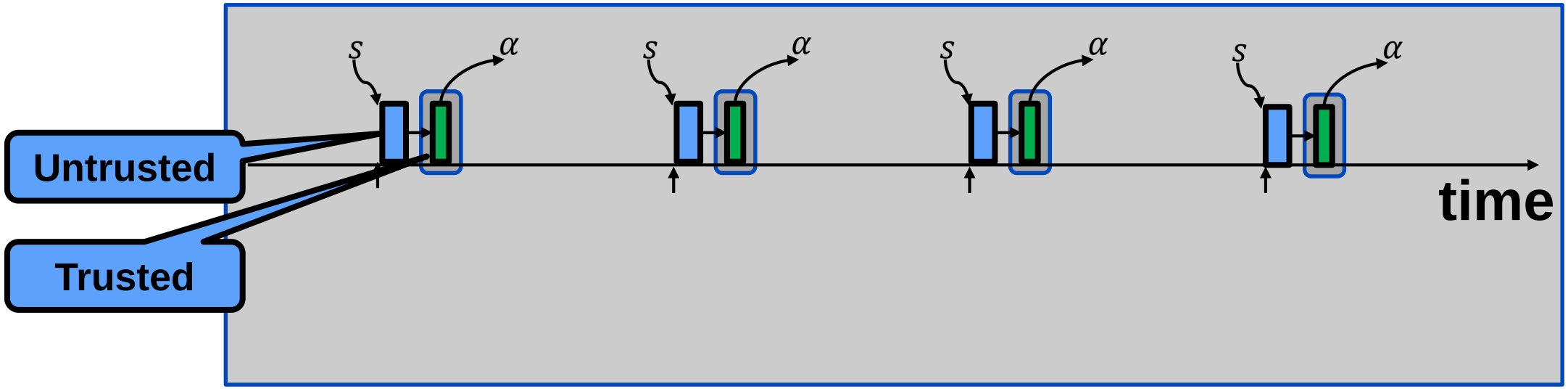
Timing can still be corrupted

- Guaranteed correct value
- BUT potentially at wrong time

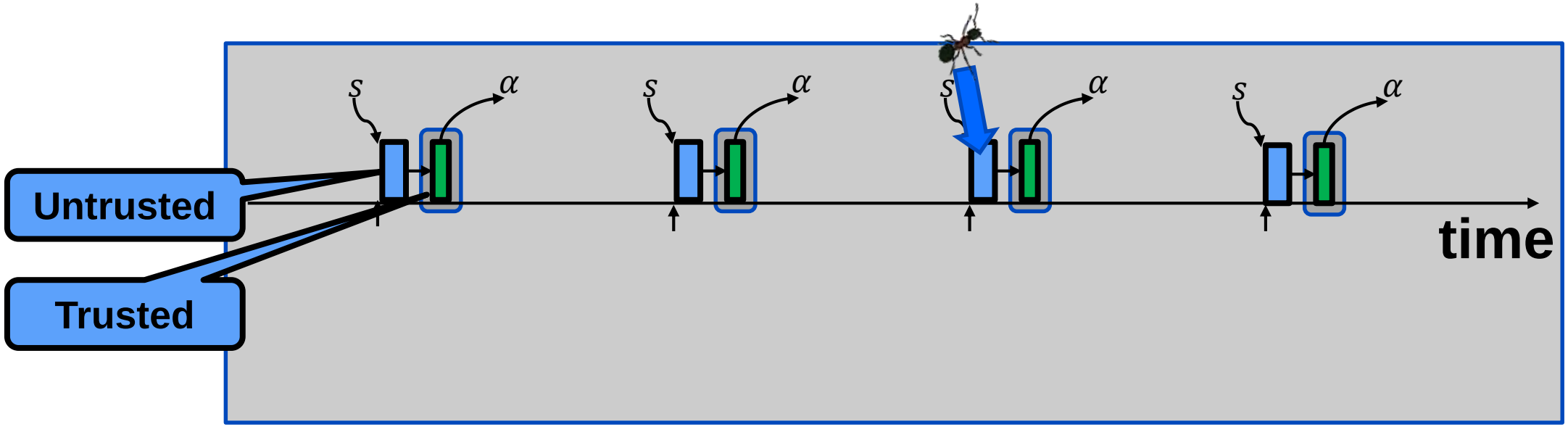
Trusted timely actuation

- Tamper-proof time-triggering mechanism
- In sync with periodic controller
- In sync with expected untrusted

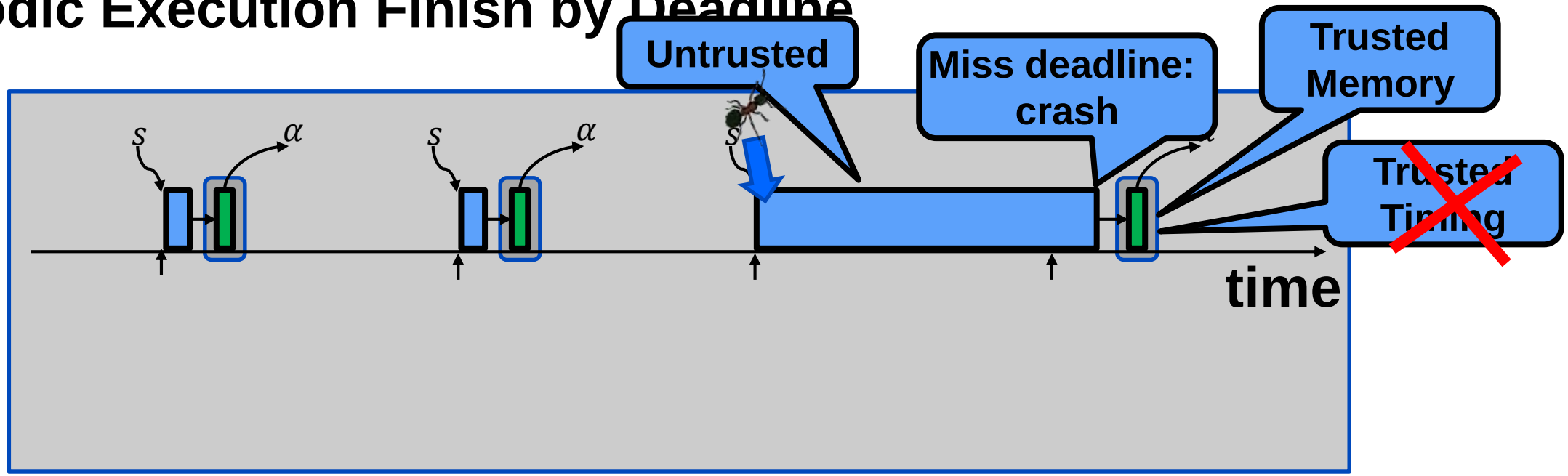
Periodic Execution Must Finish by Deadline



Periodic Execution Must Finish by Deadline



Periodic Execution Finish by Deadline



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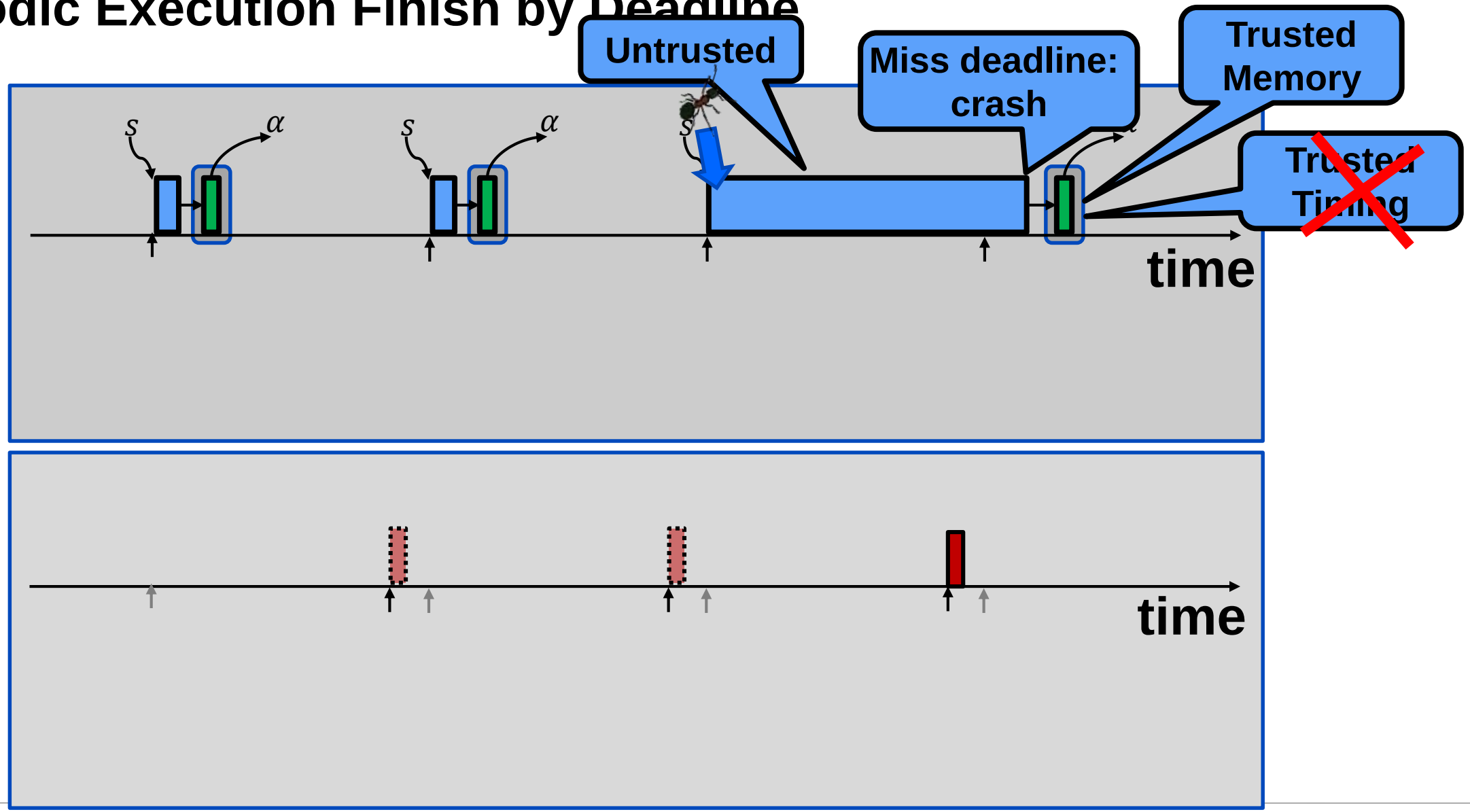
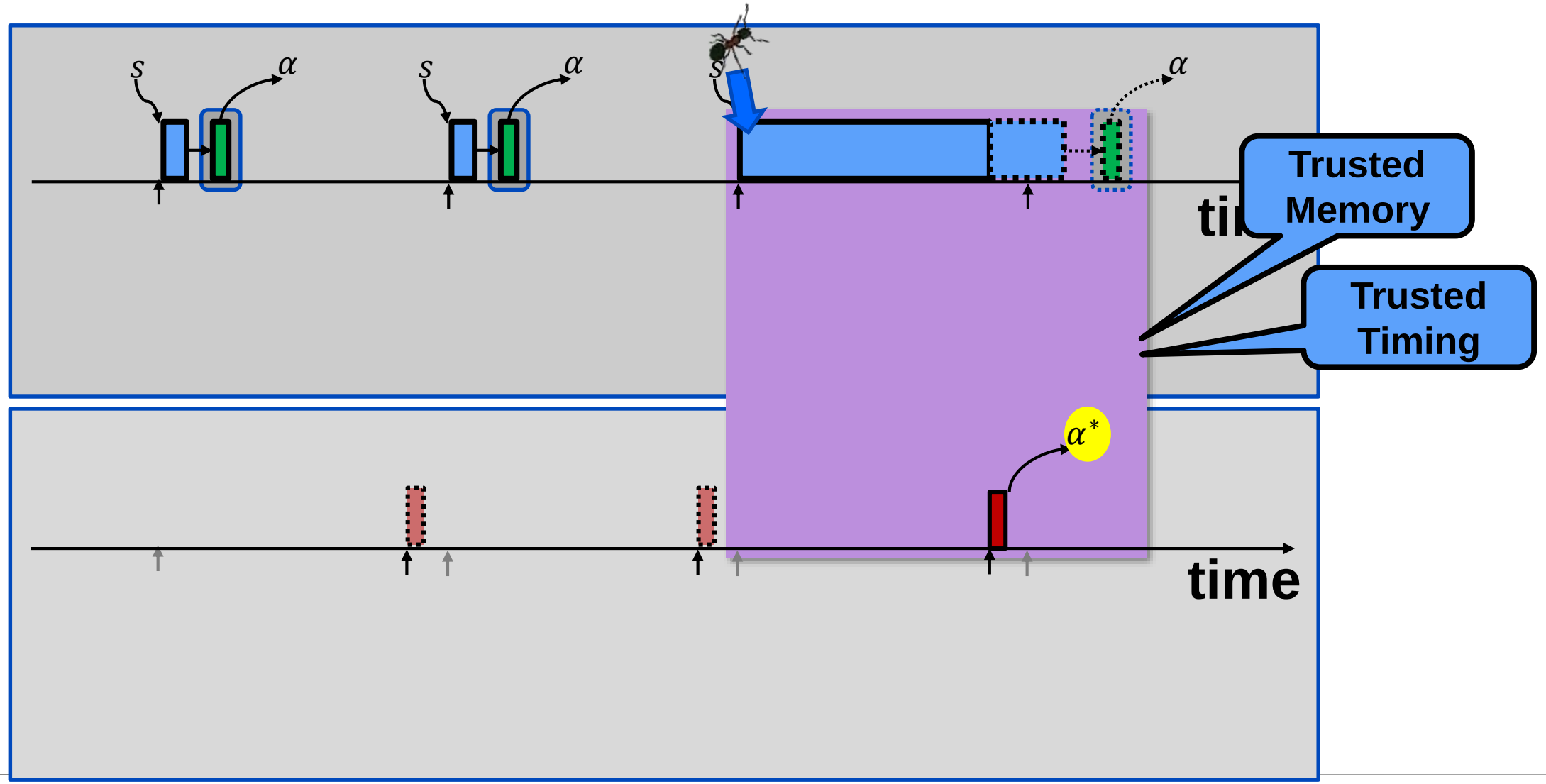
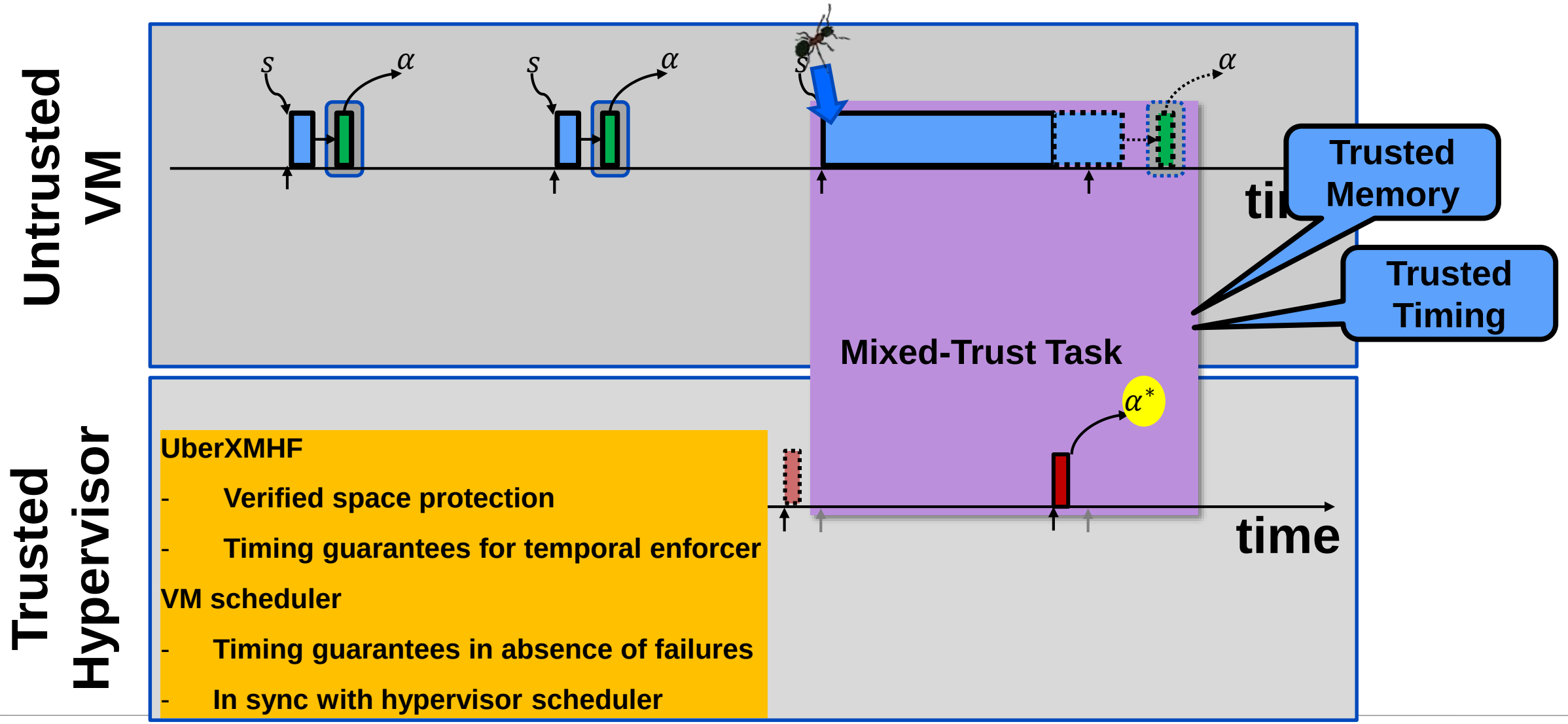


Periodic Execution Finish by Deadline



Real-Time Mixed-Trust Computation



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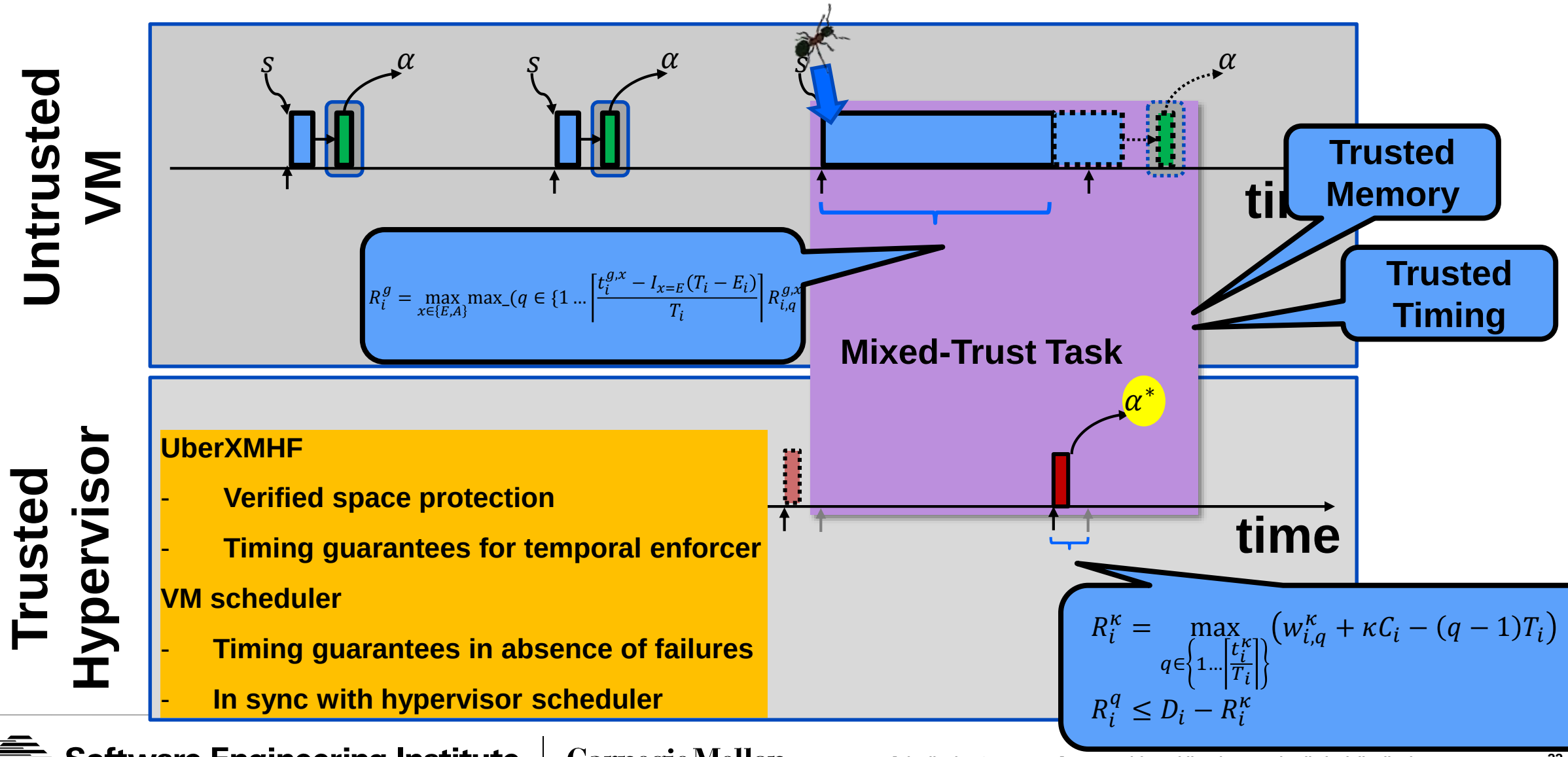

Concluding Remarks

Scaling up:

- Minimize Code to Verify
- Enforcers

Focus on key properties:

- Safety

Combined Relevant Scientific Domains

- Timing
- Logic
- Physics (Control)

Verification only effective if protected!

- Verified Protection: Hypervisor