Assured Reconfiguration: An Architectural Core For System Dependability

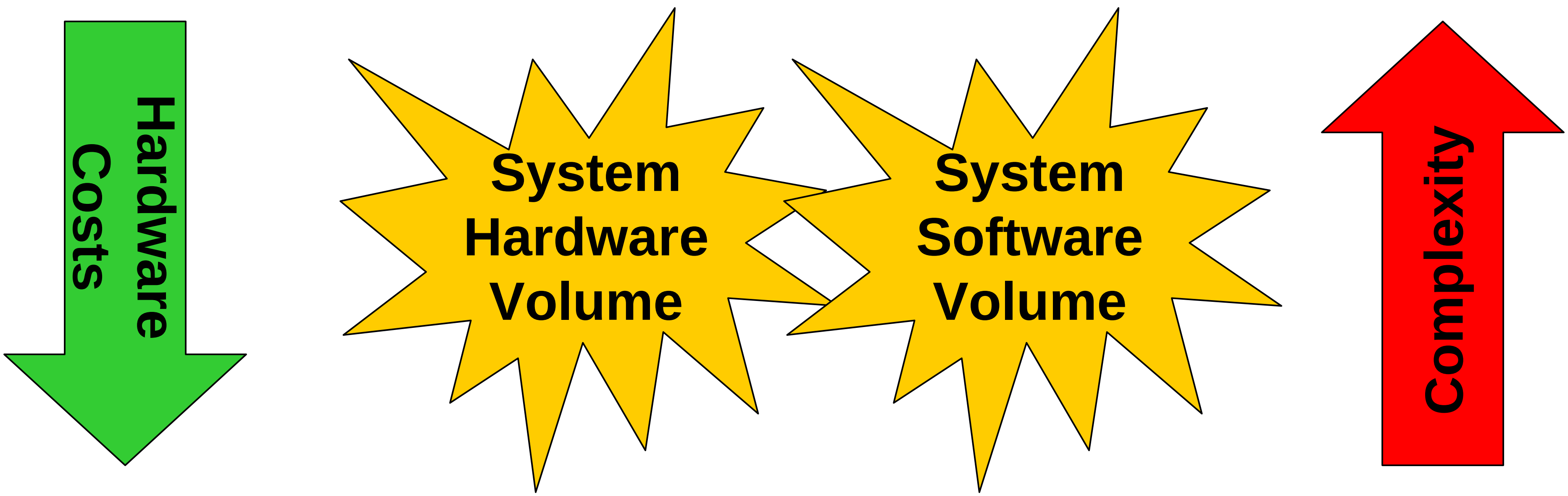
ICSE 2005
Workshop on Architecting Dependable Systems

John Knight
University of Virginia

Joint work with Elisabeth Strunk

The Challenge

Safety-Critical Applications



Implications Of The Challenge

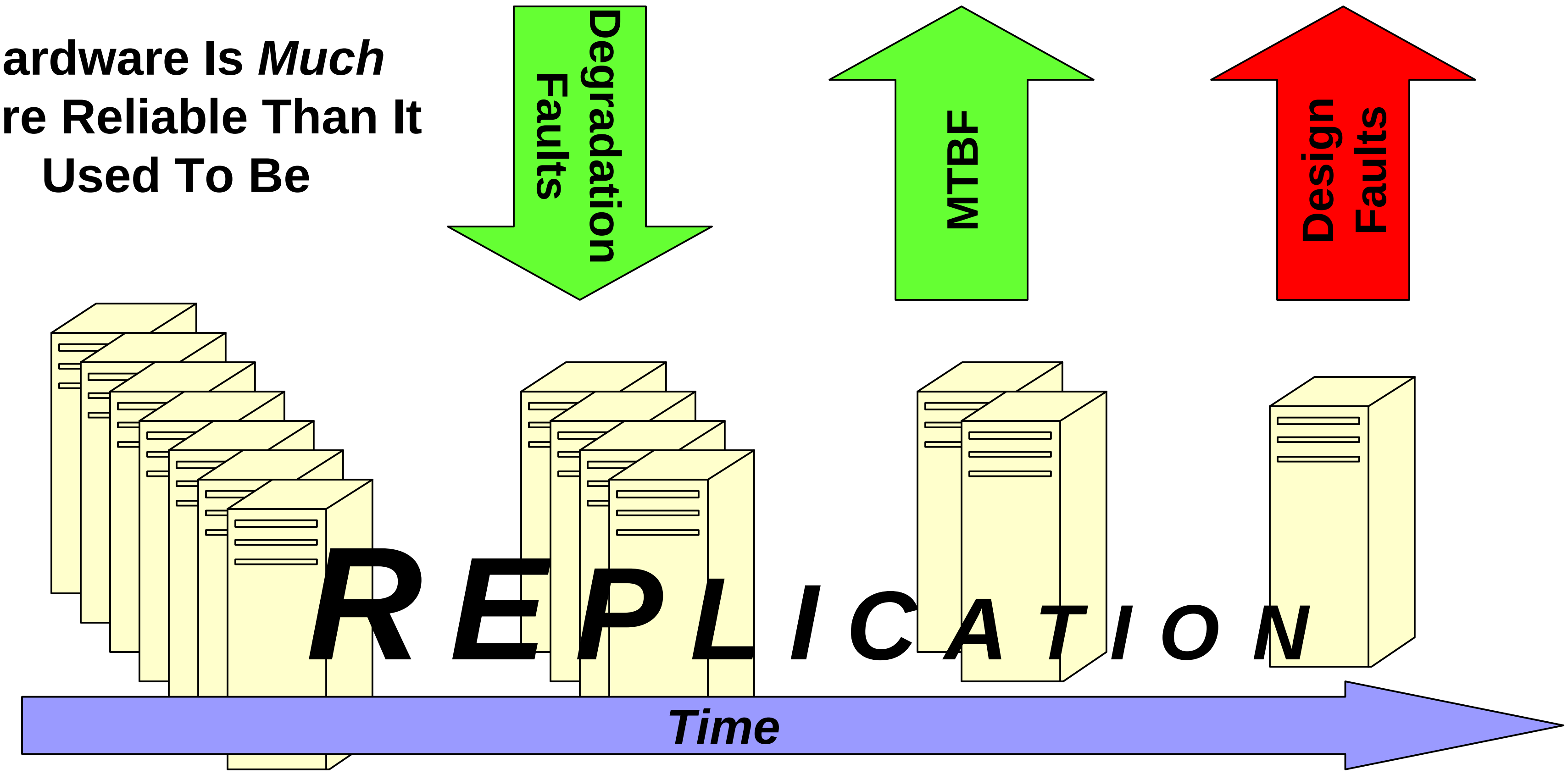
- System:
  - Distributed processing/Integrated Modular Avionics
  - High data communications demand
- Hardware:
  - Replication to meet MTBF demands
- Software:
  - Increased volume, complexity, functionality
- And it is bound to continue for the foreseeable future…

Meeting The Challenge?

- All defects can have serious consequences in typical systems but…
- Hardware replication:
  - Expensive, bulky
  - Increased weight, power, space, shielding
- Software complexity:
  - Mostly outside the realm of assurance techniques
- Trying to deal with this by ***restricting*** amount of function in systems is naïve
- Can we continue with "business as usual"?

Business As Usual For *Hardware*?

Hardware Is *Much* More Reliable Than It Used To Be



- Business as usual unnecessary

Business As Usual For *Software*?

- Why is software so difficult?
  - Fluid mechanics:
    - Continuous mathematics
    - Navier-Stokes equation
  - Structural analysis:
    - Continuous mathematics
    - Finite element method
  - Software:
    - Discrete mathematics
    - ?
- Business as usual unlikely to succeed

(Fluid mechanics and structural analysis:) Development Based On Analysis

Claim

Hardware Degradation Faults Are Much Less Frequent Than In The Past

Maintaining *Complete* Functionality With Ultra High Assurance Is Unnecessary

***Occasional* Operation With Reduced But Safe Functionality Is Satisfactory**

Basing System Design On These Assumptions Reduces Complexity And Cost

ASSURED RECONFIGURATION

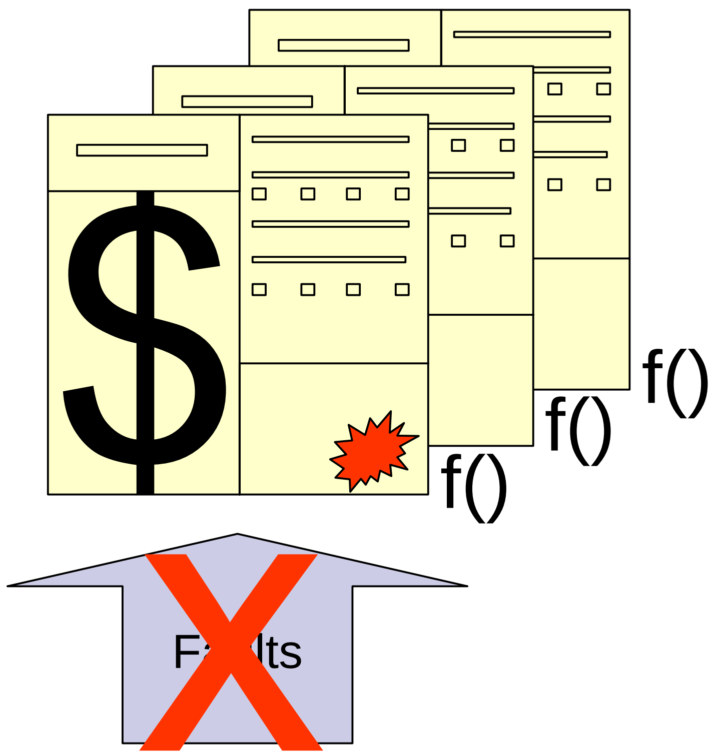
What Is Assured Reconfiguration?

- ***Explicit decision at specification level*** to define a tradeoff between system dependability and function
- ***Explicit decision by system stakeholders*** to accept alternative functionality if errors do occur
- ***Because***:
  - Complete hardware masking is too expensive
  - *Adequate software fault avoidance/removal is infeasible*

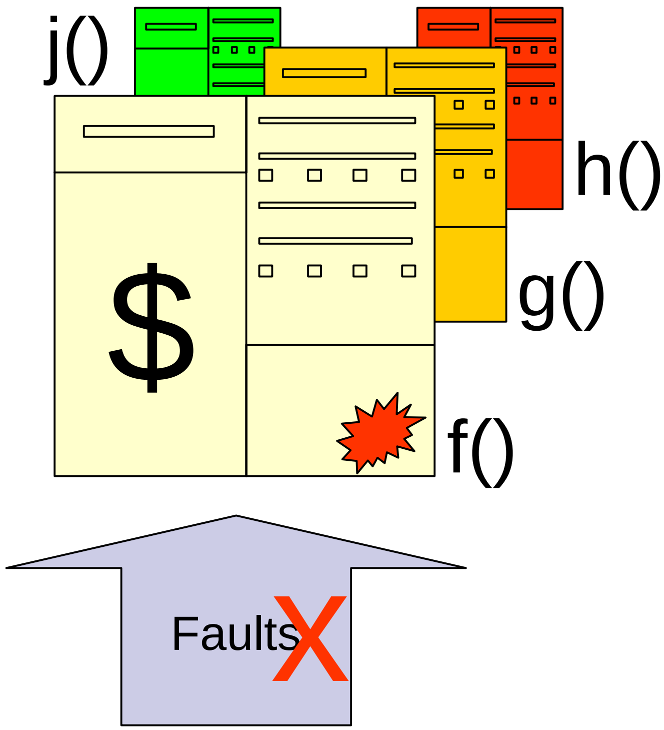
Common Cases

What Is Assured Reconfiguration?

Reliability, Availability



Assured Reconfiguration



Target Configuration Depends On Conditions

Example: Modern Avionics Systems

- Aircraft flight control ***software***
- FAA software development standard:
  - Minor:
    - Anticipated to occur one or more times during the entire operational life of each airplane
  - Major:
    - Not anticipated to occur during the entire operational life of a single random airplane
  - Catastrophic:
    - Not anticipated to occur during the entire operational life of all airplanes of one type
    - Failure rate of 10^{-9} per hour of operation

Example: Modern Avionics Systems

- These requirements:
  - Cannot be assured with current approaches
  - Are essentially impossible to demonstrate
- ***But***, some (most?) functionality:
  - Does not need to be reliable
  - Needs to be *fail-stop* with ultra high dependability
- Assured reconfiguration is an option to achieve system goals

Prior Work on Reconfiguration

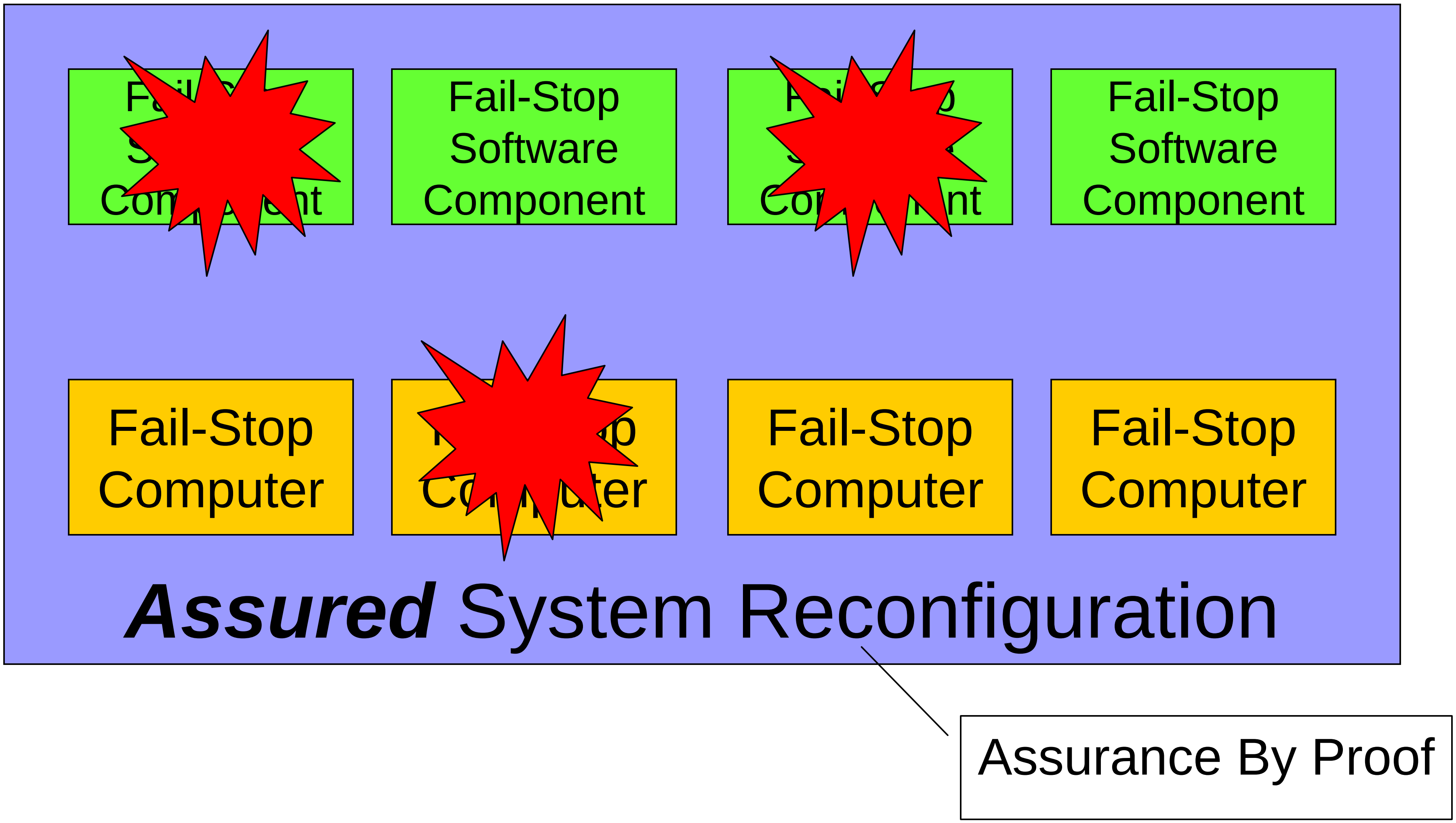
- Survivability in critical information systems
  - Different requirements for embedded systems
- Alternative functionalities (Shelton and Koopman)
  - Provides a model of system utility
- Graceful degradation
  - Maximum utility with working components

Prior Work on Reconfiguration

- Quality of service
  - Specific aspects of a system
- Simplex architecture (Sha)
  - Assumes analytic redundancy
- Current systems, e.g., Boeing 777
  - Ad-hoc
  - Are built using facilities already provided by the system

Vision

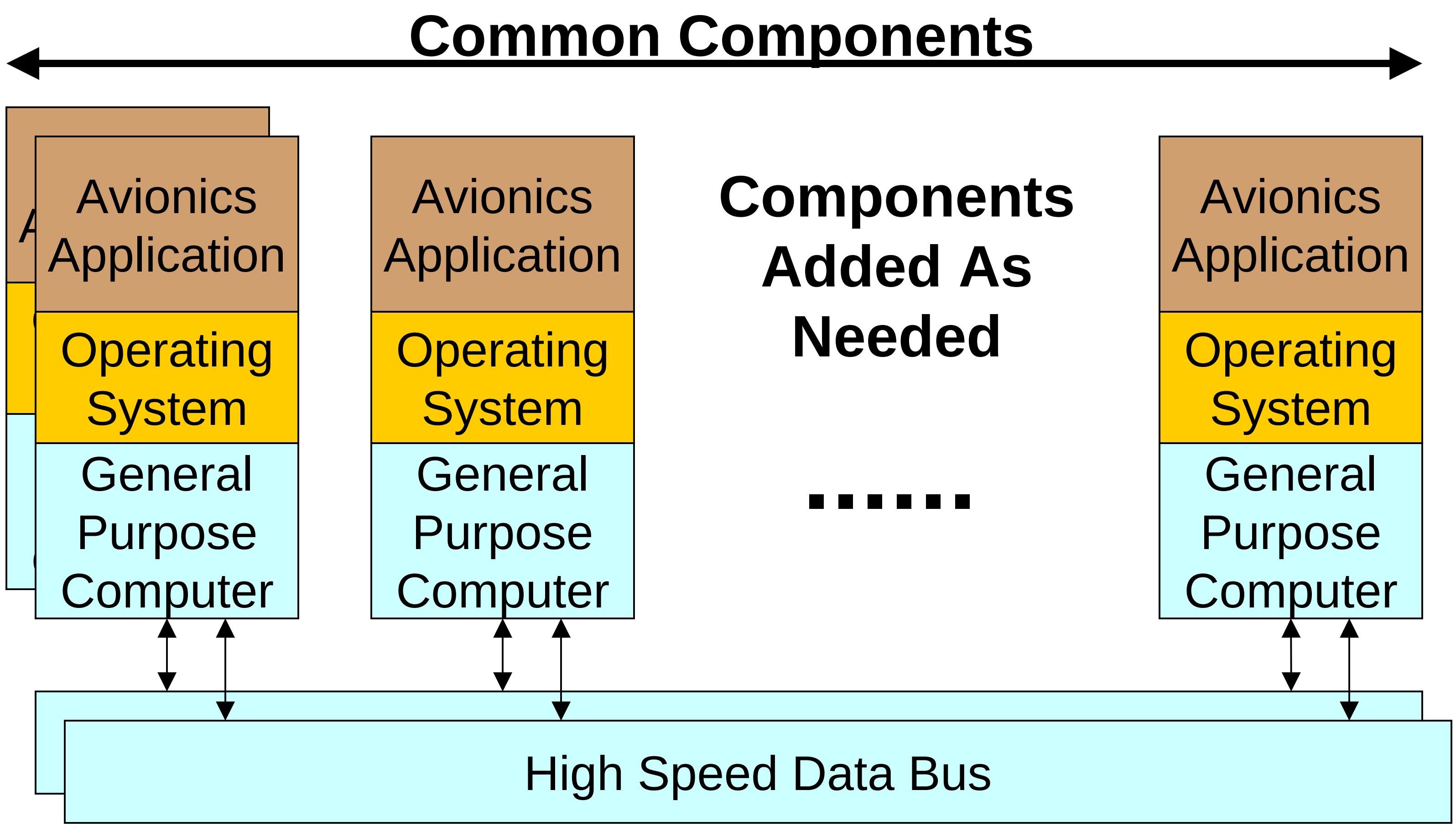
Reconfiguration As Architectural Foundation



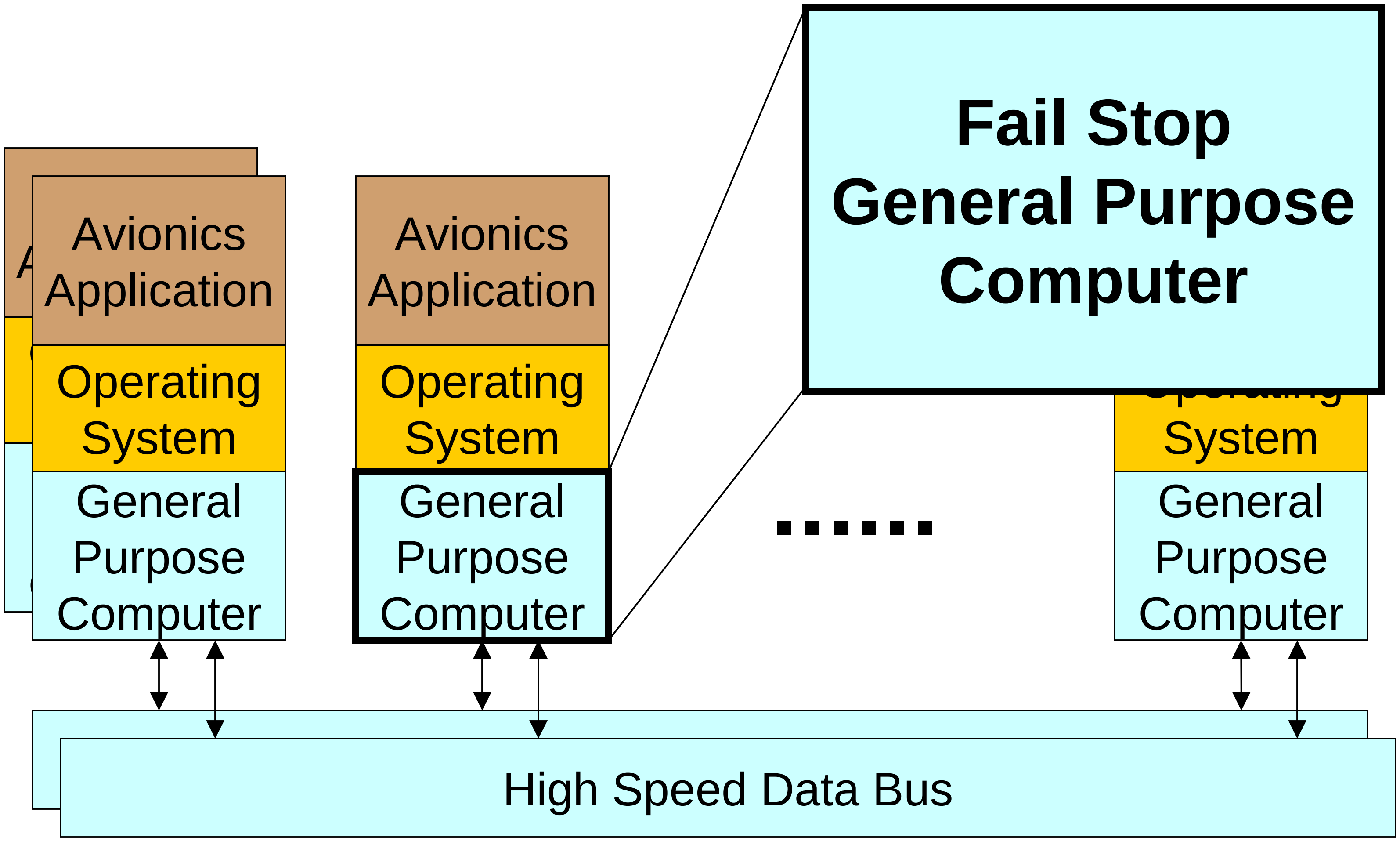
Proposed Approach

- System architecture:
  - Fully distributed, arbitrary layout and number of parts
  - Ultra-dependable data bus, e.g., TTP
- Computing and storage hardware:
  - Allow computers to fail, ***but***
  - Use ultra-dependable fail-stop machines
- Software:
  - Allow application software to fail, ***but***
  - Use ultra-dependable, fail-stop applications
- ***Ultra-dependable reconfiguration mechanism***

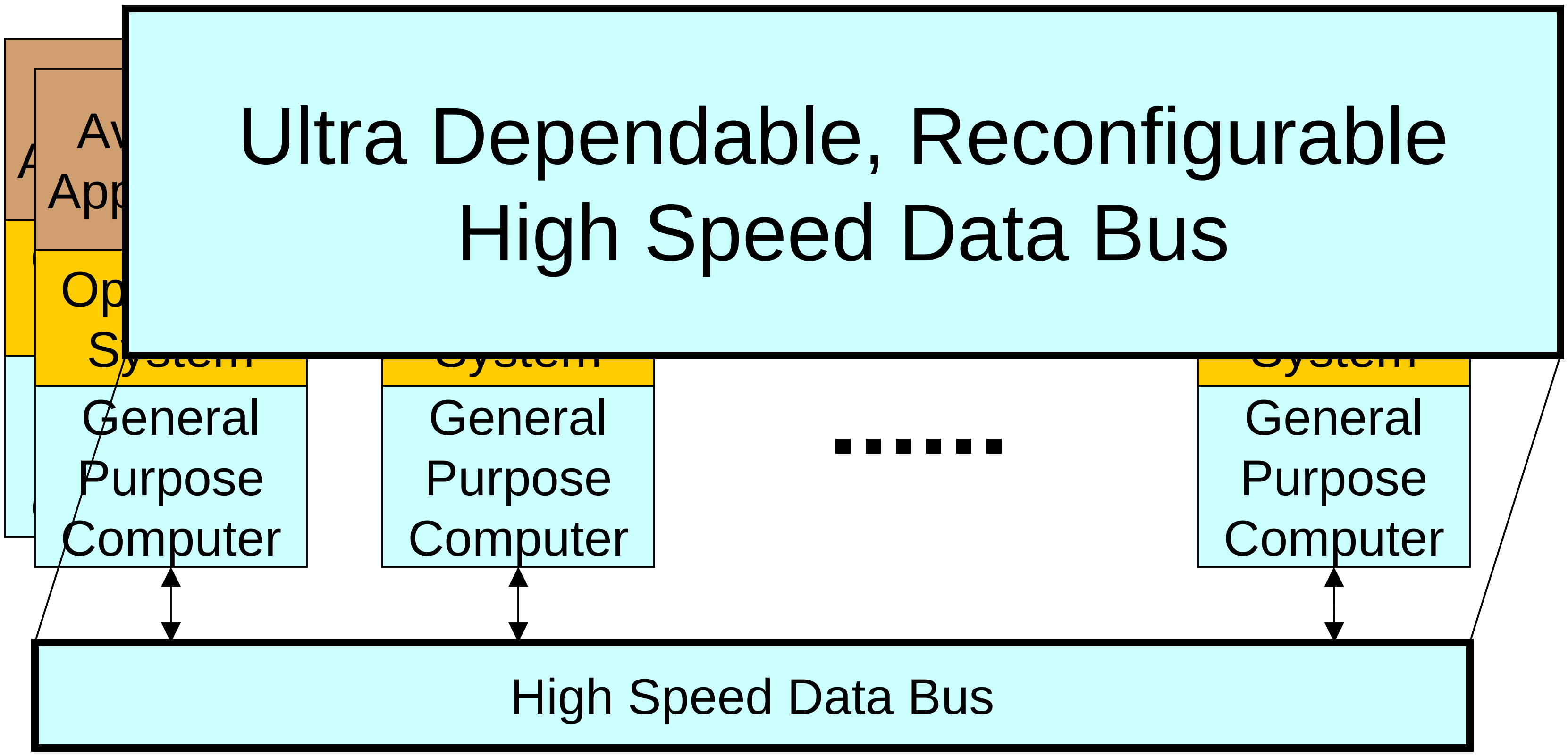
Proposed Approach



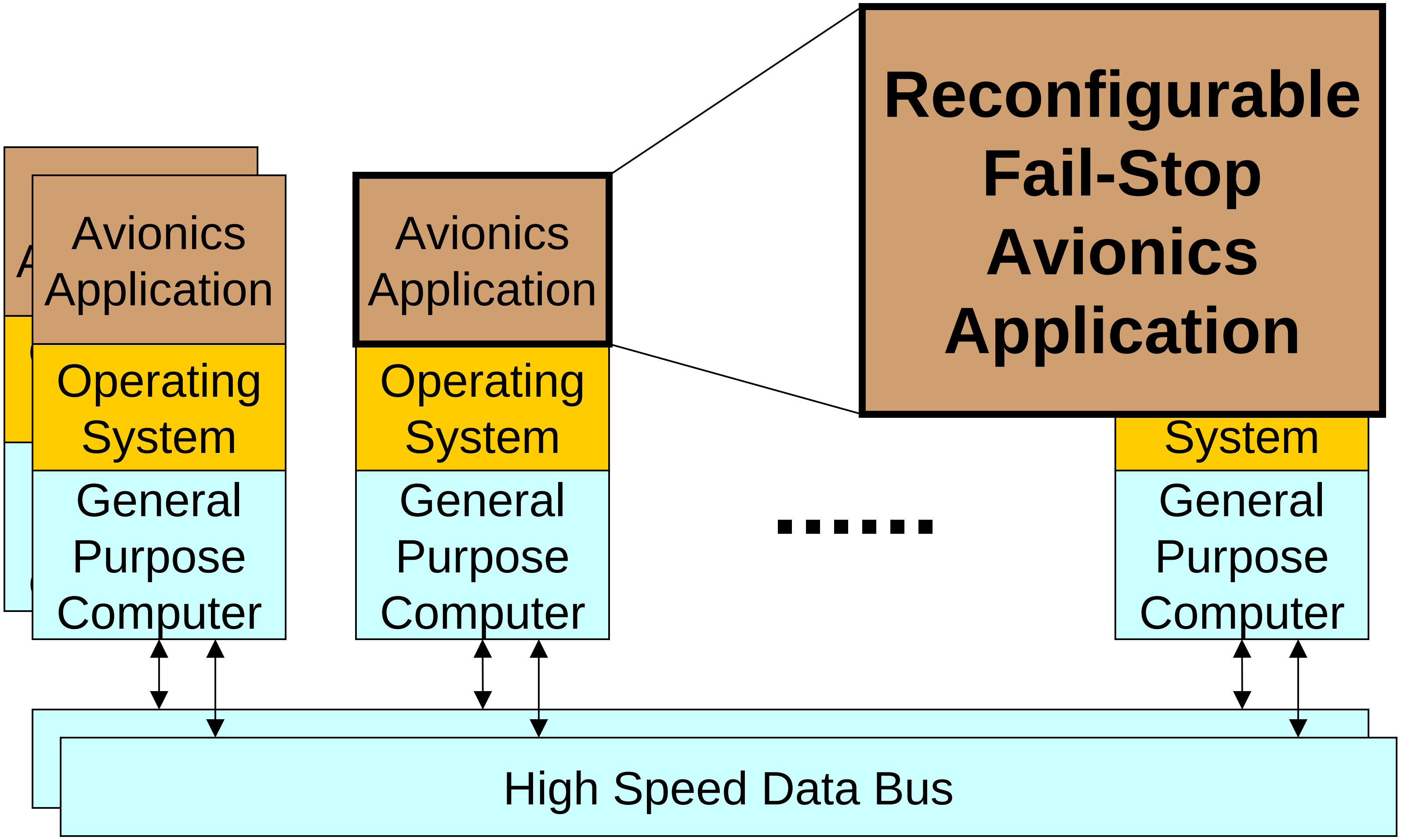
Proposed Approach



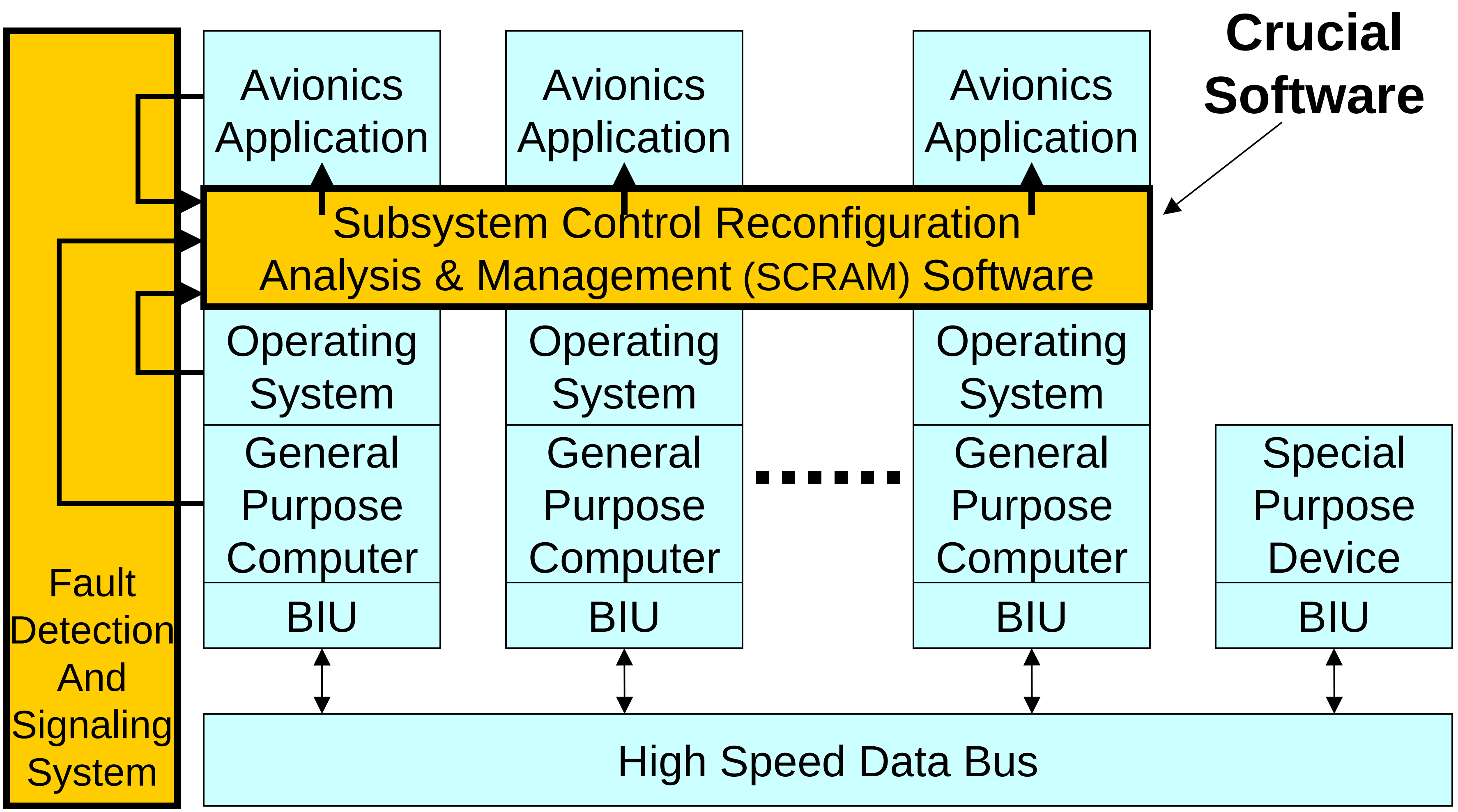
Proposed Approach



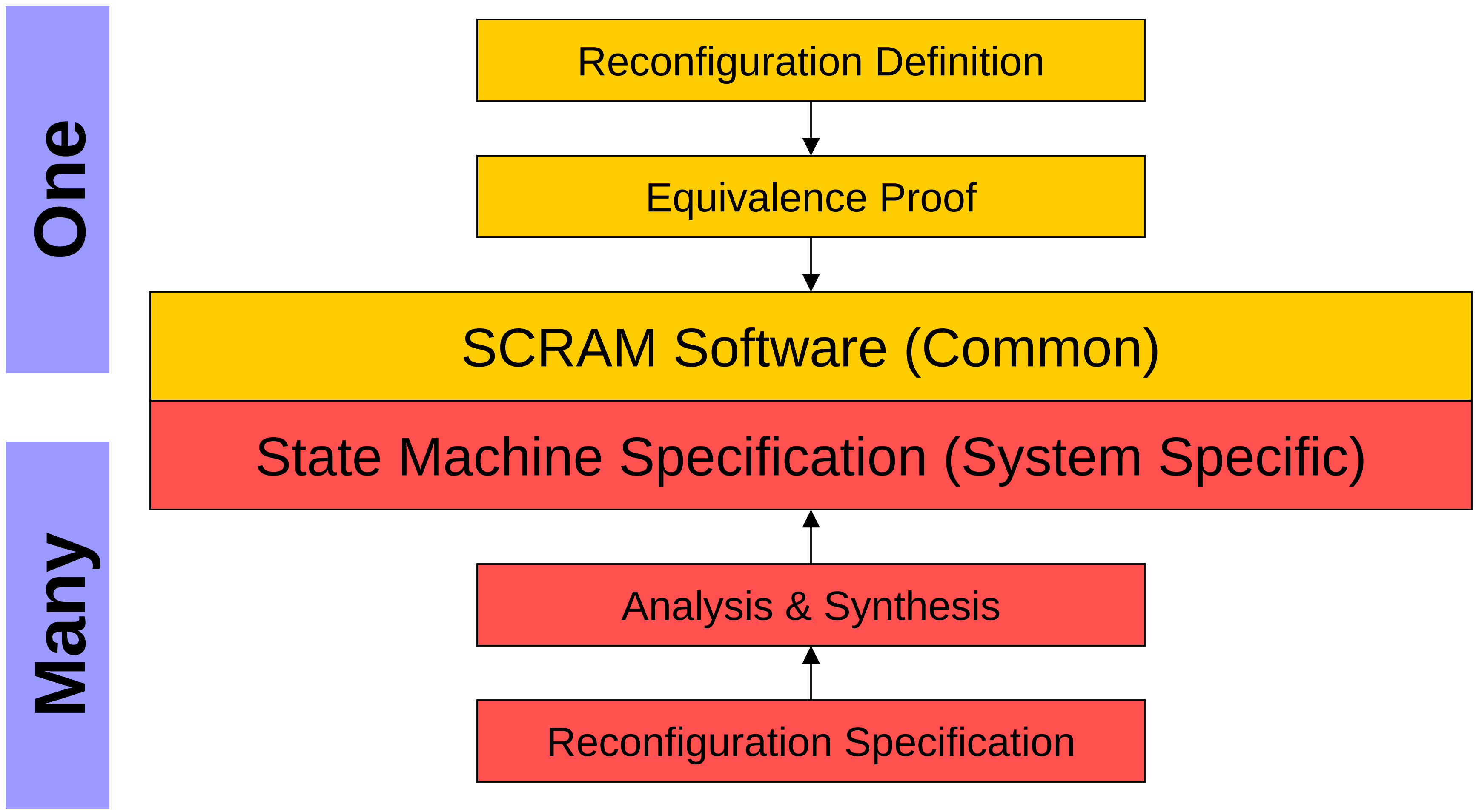
Proposed Approach



Distributed Reconfigurable System Architecture



Crucial Software Development



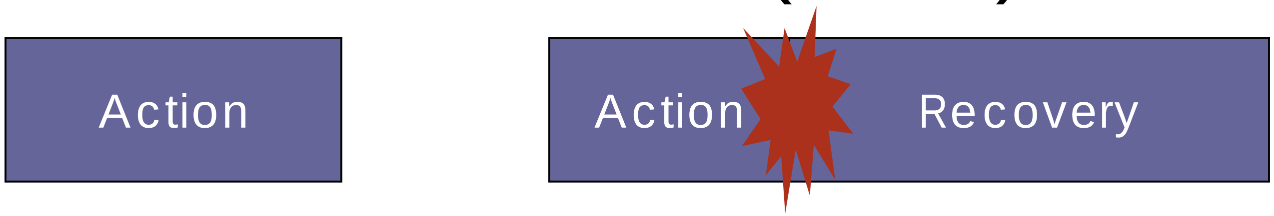
Application Programming

Fail-Stop Processors

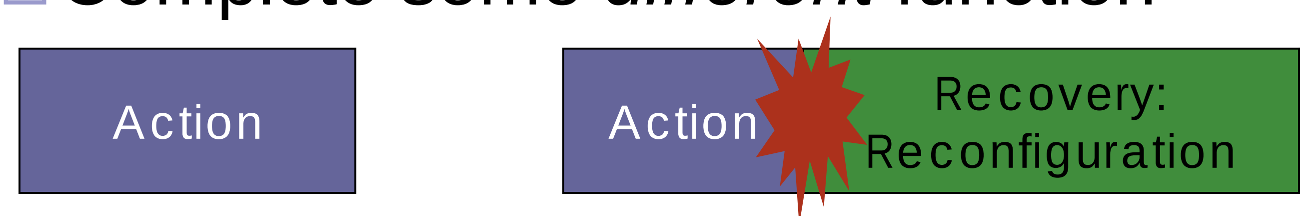
- Introduced by Schlichting and Schneider
- Building block for critical systems
- Fail-stop processor:
  - Processing units
  - Volatile storage
  - Stable storage
- Stable storage preserved on failure

Reconfigurable FTAs

- Fault-tolerant actions (FTAs)



- In S&S work, recovery must complete original action
- In our work, recovery could be reconfiguration
  - Complete some *different* function



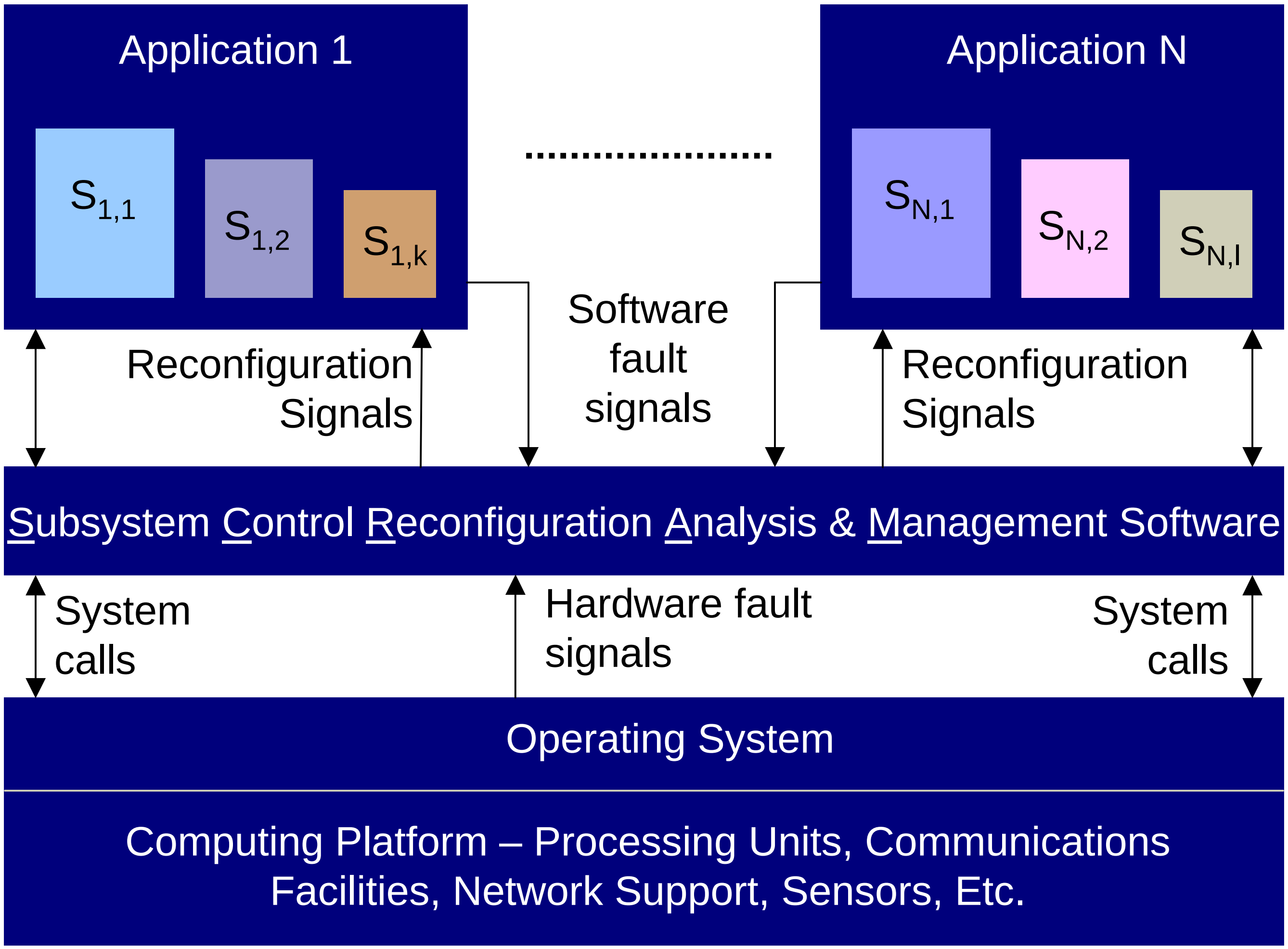
Reconfigurable Fail-Stop Systems

- Software building block is a *reconfigurable application*
- Reconfigurable application has:
  - A predetermined set of specifications
  - A predetermined set of FTAs for each specification
- Application function exists in system context:
  - Recovery must be appropriate to system
  - Failure in one application could cause failure in another
- Not a problem in S&S work since failures were masked, sufficient resources assumed

Application and ***System*** FTAs

- *Application* FTAs
  - Execution of a single application
- *System* FTAs
  - Composed of a set of AFTAs
    - Affected applications' actions and recovery protocols
    - Standard AFTAs for the other applications
  - Coordinates stages of AFTAs
  - Stages have time bounds
  - S & S can guarantee liveness
  - Safe configuration enables real-time guarantees

Reconfiguration Software Architecture



Specifications

$S_{i,1}$: desired functionality

$S_{i,2}$: intermediate functionality

…

$S_{i,m}$: crucial functionality

Reconfiguration Assurance

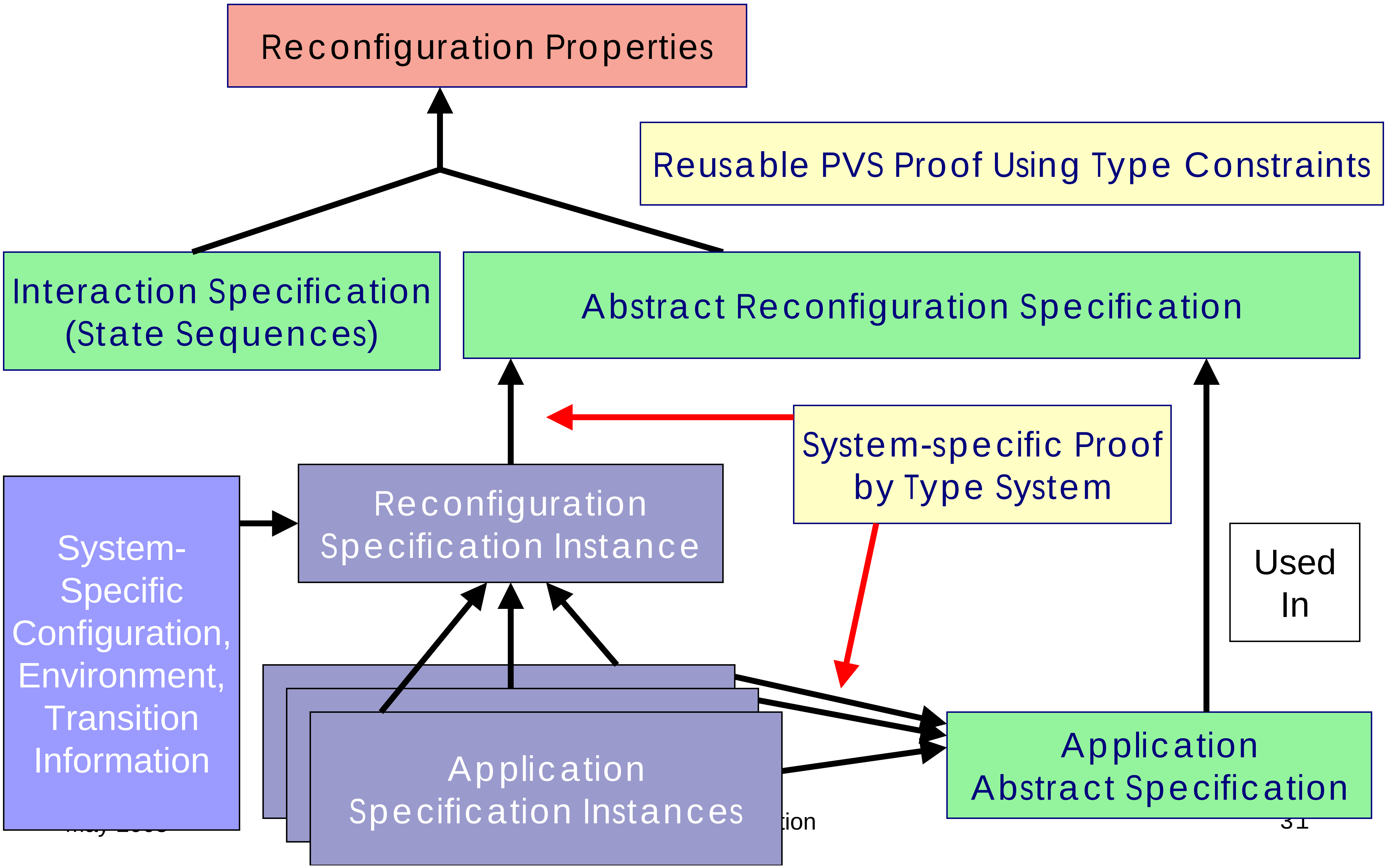
Reconfiguration Properties

- Reconfiguration:
  - Begins with a signal generated by some application
  - Ends either with a second signal, or when all applications have finished initialization
- The new configuration is appropriate for the circumstances
- All reconfigurations complete within their required time bound
- The system invariant holds during reconfiguration
- Additional restriction on sequences of reconfiguration signals

Assurance Technology

- Based on PVS specification notation and PVS theorem-proving system
- PVS:
  - Language is a higher-order logic based on type theory
  - Subtypes are defined by adding a predicate to a supertype
  - Predicate must hold over any instance of subtype
  - Type properties can be used in proofs
  - In some cases, type properties are undecidable
  - Produces type-correctness conditions (TCCs), a kind of proof obligation
  - PVS system mechanically checks proofs

Proof Structure



Reconfiguration Specification

- System applications
- Operating environment
- System configurations
- System transitions
- Valid system implementation generates a valid sequence of system states

Proof Sample

- **Proofs are scripts that can be mechanically checked using the PVS system**

```
assured_reconfig.CP5: proved - complete [shostak](13048.43 s)

(""
 (skosimp)
 (split)
 (("1"
   (lemma "reconf_length")
   (inst -1 "s!1" "r!1")
   (typepred "r!1")
   (typepred "s!1`tr")
   (expand "get_reconfigs")
   (hide -2 -3 -4)
   (flatten)
   (case "r!1`end_c - r!1`start_c = 1")
   (("1"
     (lemma "reconf_halt")
     (expand "reconfig_end?")
     (split -6)
     (("1"
       (expand "reconfig_start?")
       (skosimp)
       (inst -1 "app!1")
       (inst -2 "s!1" "r!1" "app!1")
       (hide -4 -5 -6 -7 -8)
       (grind))
      ("2" (propax))))
    ("2"
```

Reconfiguration Example

Example

- UAV system
- Four applications:
  - Sensors, flight control system
  - Autopilot, pilot interface
- Complete reconfiguration interface, multiple functionalities
- Three reconfiguration triggers:
  - Electrical power
  - Rudder
  - Autopilot

Example Configurations

Configuration	Power	Rudder	Autopilot	FCS
Full Service	alternator	working	normal	normal
Altitude Hold Only	alternator	working	altitude hold only	normal
Flight Control Only	alternator	working	nonfunctional	normal
Flight Control Only	battery	working	disabled	normal
Rudder Hard-Over L/R	alternator	hard-over left/right	normal	adjusting for rudder
Rudder Hard-Over L/R, Altitude Hold Only	alternator	hard-over left/right	altitude hold only	adjusting for rudder
Rudder Hard-Over L/R, Flight Control Only	alternator	hard-over left/right	nonfunctional	adjusting for rudder
Rudder Hard-Over L/R, Flight Control Only	battery	hard-over left/right	disabled	adjusting for rudder

Example SFTA

In Full Service configuration when the rudder becomes stuck hard-over to the left

Frame	Action	Predicate
1 (start)	Sensors: signal generated All other apps: normal execution	Sensors: invariant All other apps: invariant
2	Apps anticipate possible reconfiguration	App postconditions
3	FCS: prepare to adjust for rudder All other apps: normal execution	FCS: transition condition All other apps: invariant
4 (end)	All apps: normal execution	All apps: invariant

Example Status

- Specified in PVS
- Type-checked against the abstract specification
- 75 TCCs generated
  - Most resulted from specific PVS approach
  - Most others trivial to prove
  - Nontrivial proofs could be generated using state-space search
  - Proofs could be more difficult for larger systems
- Proof obligations discharged
  - Reconfiguration properties hold

Conclusion

- Exploit potential of fully distributed target
- Hardware MTBFs:
  - Much higher
  - Less replication needed, accept rare failures
- Software Volume:
  - Increasing and assurance remains difficult
  - Fail-stop software less difficult to develop
- Base architecture on assured reconfiguration
- Assurance via comprehensive formal proof

Contact Information

- John Knight – knight@cs.virginia.edu
- Elisabeth Strunk – strunk@cs.virginia.edu

- Papers available at:

  http://www.cs.virginia.edu/~jck/recentpapers.htm