Mission Data System

An end-to-end platform for high dependability autonomous monitoring and control of physical systems

HDCP Workshop
May 29–30, 2002

DRAFT

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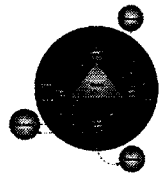
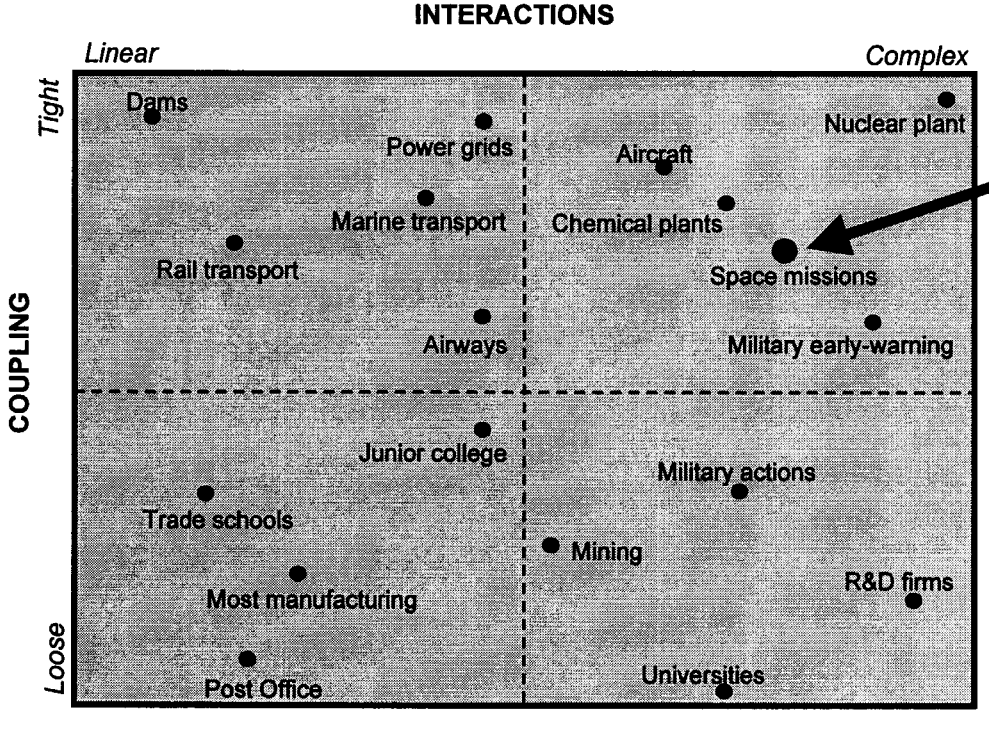
Preface



- MDS addresses autonomous monitoring and control of physical systems
- MDS has a broad scope:
  - A systems engineering process
  - A matching software architecture of two dimensions:
    - A state- and goal-based architecture for monitoring and control
    - A component & connection architecture for software engineering
  - Core framework software
  - Iterative development process
- Opportunities for improving dependability exist in all 4 areas

Origins of MDS

- MDS conceived as a unified flight / ground / test architecture for unmanned space science missions
- Systems are high-risk due to complex interactions and tight coupling; space is an unforgiving environment



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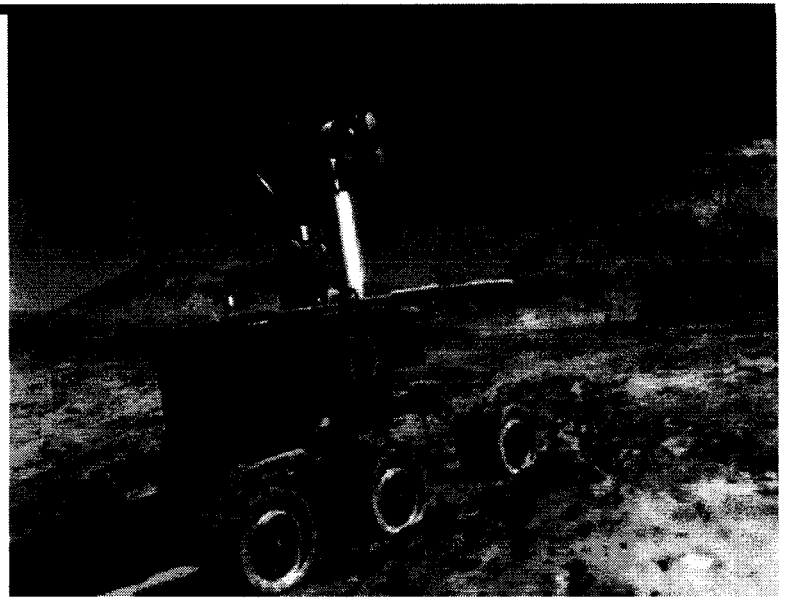
From *Normal Accidents: Living with High-Risk Technologies*, by Charles Perrow, 1984.

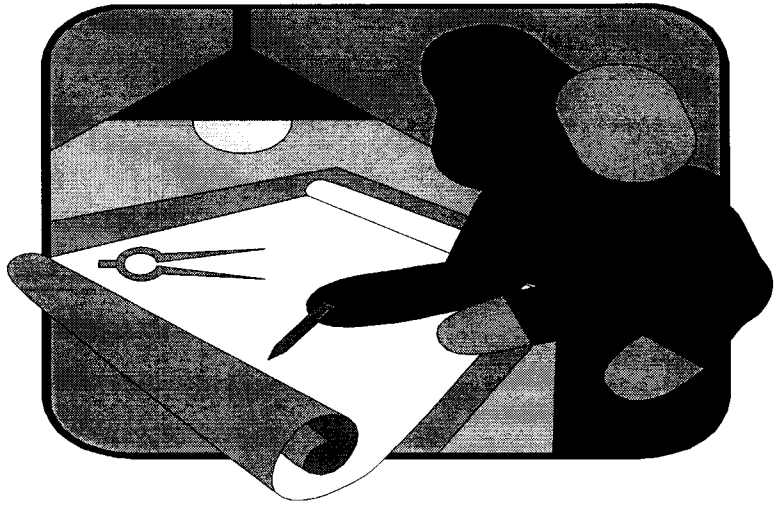
MDS Problem Domain



- Autonomous monitoring and control of physical systems
  - Mobile robots (spacecraft, planetary rovers, lawn mowers, ...)
  - Immobile robots (manufacturing robots, industrial process control, toasters, ...)
  - Vast sensor/actuator web: "The Edge" of the world-wide web
- Scope includes:
  - Real-time control and estimation
  - Deliberative planning and scheduling of goals
  - Management of engineering and science data
  - Infrequent data transport across links having huge round-trip delays
  - Modeling of complex interactions
  - Reactive control, including fault protection, at multiple time scales
  - Management of many limited resources (power, memory, pointing, ...)
  - Human operation/monitoring of autonomous agents

MDS Approach & Scope

- Apply *product line practice* to:
  - Exploit commonalities across products
  - Reduce cycle time and costs
  - Improve reliability



- Scope includes:
  - Systems engineering analysis & design process
    - Collaborative, iterative analysis & design & refinement captured in a structured form
  - State architecture
    - States, goals, models, estimators, controllers, measurements, commands, ...
  - Component architecture
    - Components, interfaces, ports, connections, roles, configuration, rules, ...
  - Core framework software
    - State variables, goal networks, time services, data catalog, logging, naming, units, ...
  - Iterative build & test process
    - Work packages, package promotion, daily builds, baselines, test cases, ...

MDS Products

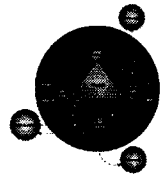
MDS customers will get...

1. **Unified flight, ground and test architecture**
   - Based on several broad organizing themes
2. **Orderly systems engineering methodology**
   - Bridging the gaps from analysis to requirements to software design to operations
3. **Object-oriented design**
   - Comprised of classes, templates, patterns, test scenarios, and so on, described in the Unified Modeling Language
4. **Frameworks**
   - Core infrastructure *and* discipline-specific sets of classes, algorithms, and models adaptable to a variety of missions
5. **Processes, tools, and documentation**
   - Integrated development, test and simulation environments and guidelines, monitoring, diagnosis and verification tools, adapters guides, and so on
6. **Examples**
   - Executable instantiations of frameworks that will serve as examples for real applications
7. **Reusable software**
   - An expanding legacy of code easily applied to successive missions

Architectural Themes

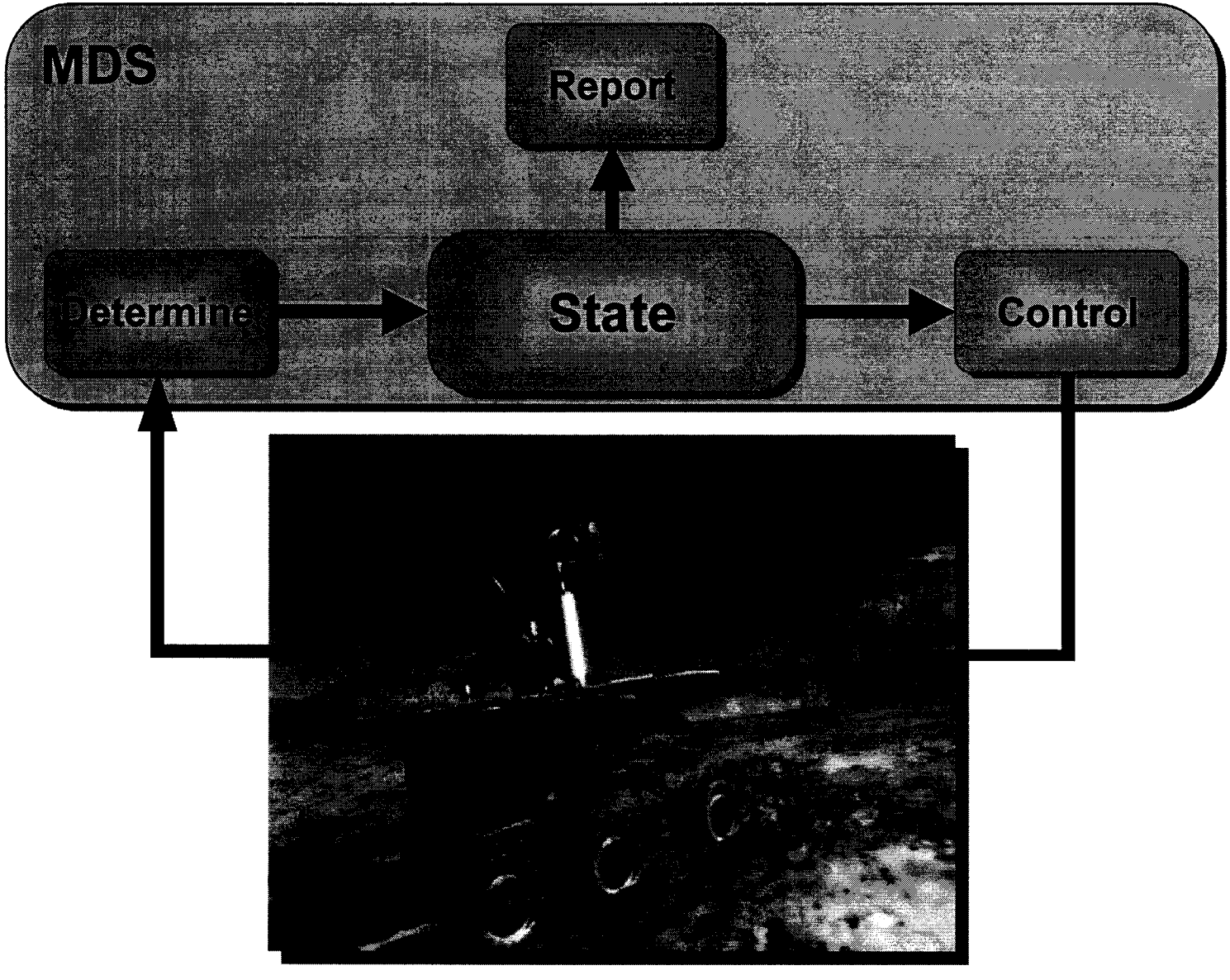
- Formal representation and manipulation of state are central
- State uncertainty is acknowledged and used in decision making
- Goal-based operation specifies intent; simplifies operations
- Express domain knowledge in models, not program logic
- Closed-loop control for in situ reaction to events
- Fault protection is integral part of design, not an add-on
- Real-time resource management (for power, fuel, etc.)
- Clean separation of state determination from control
- Clean separation of data management from data transport
- Navigation and attitude control built from a common base
- Plan to migrate capability from ground to flight
- Make interactions visible/analyzable at an architectural level

"Architecture Hoisting"



- Things that are "buried in the analysis" or "buried in the code" are hard to review, analyze, modify, and manage
- In many areas MDS makes things *explicit* and brings them out into the light of day. We call this "architecture hoisting":
  - Components communicate only via connections
  - Architecture configuration is explicit and inspectable
  - Units of measurement are explicit and enforced
  - Initialization dependencies are explicit and enforced
  - State timelines make estimated and planned states visible to all
  - Operation based on explicit, unambiguous constraints on state & time
  - Synchronization at component boundary is explicit and inspectable
  - Physical interactions are explicitly represented in models
  - Resources (power, etc) are managed as state allocations
- All this explicitness offers many opportunities for improving dependability through analysis and verification

State-Based Architecture



Bridging the Gap Between Systems and Software Engineering

Systems engineers follow a disciplined "state analysis", asking & answering questions such as these:

The state architecture bridges the gap through a shared set of architectural elements

Software engineers build the system by adapting a software framework having the same architectural elements

What do you want to achieve?
Move rover to rock. → ***Goal*** → Goal Network, Simulation, …

What's the state to be controlled?
Rover position relative to rock. → ***State Variable*** → State Knowledge, Hardware Proxy, Sequential Estimation

How do you know what that is?
Measure relative position with stereo camera. → ***Measurement*** → Measurement Package, Data Catalog, Graph Library

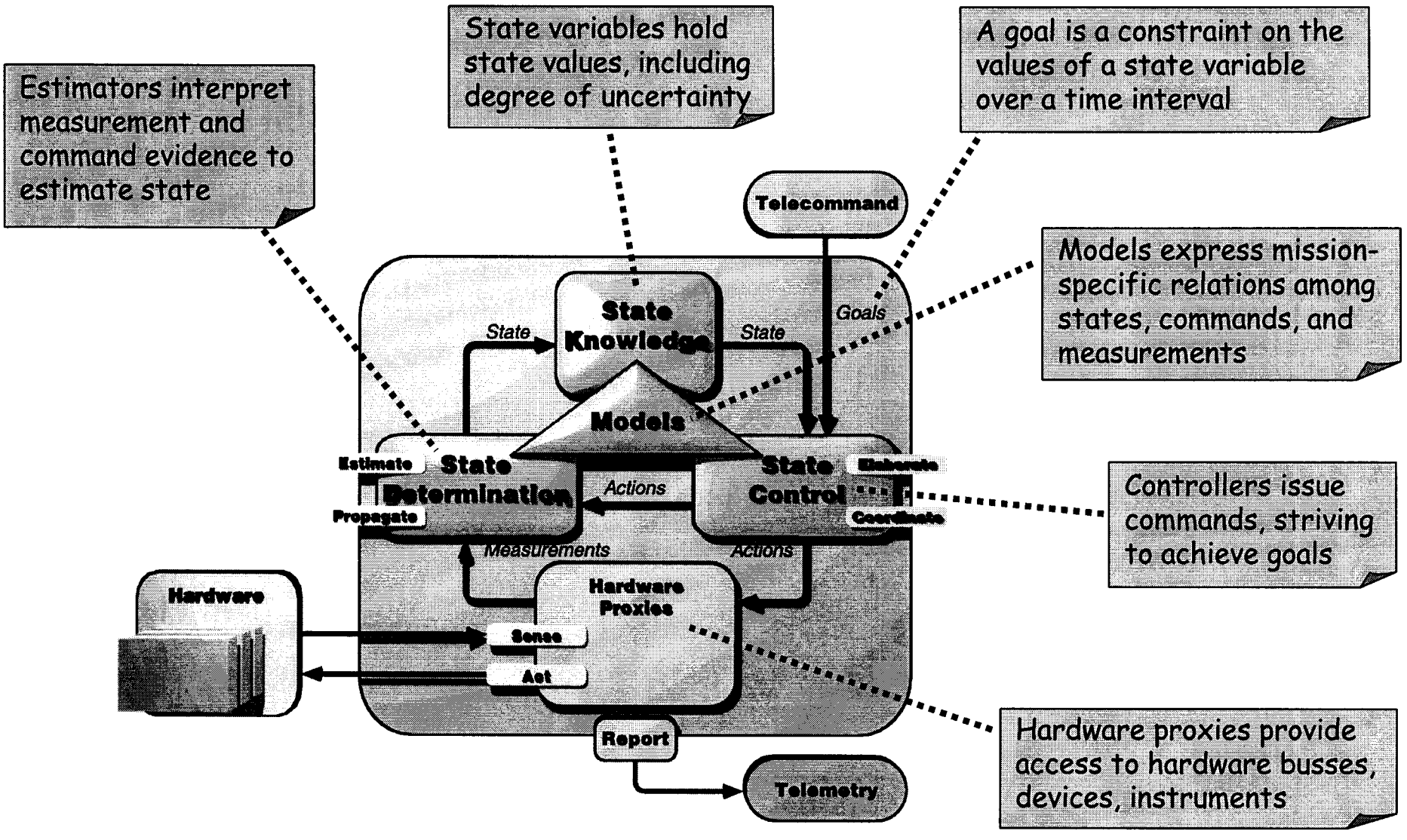
What does the stereo camera measure?
Distance to terrain features, light level, camera power (on/off), camera health. → ***Measurement Model*** → State Models, Coordinate Systems, SI Units, Naming

How do you control light level?
Wait until the sun is up. → ***State Model*** → Time Services, Linear Algebra, Event Logging

Where is sun relative to horizon?
…

Etc. → …, …, …

State-Based Architecture

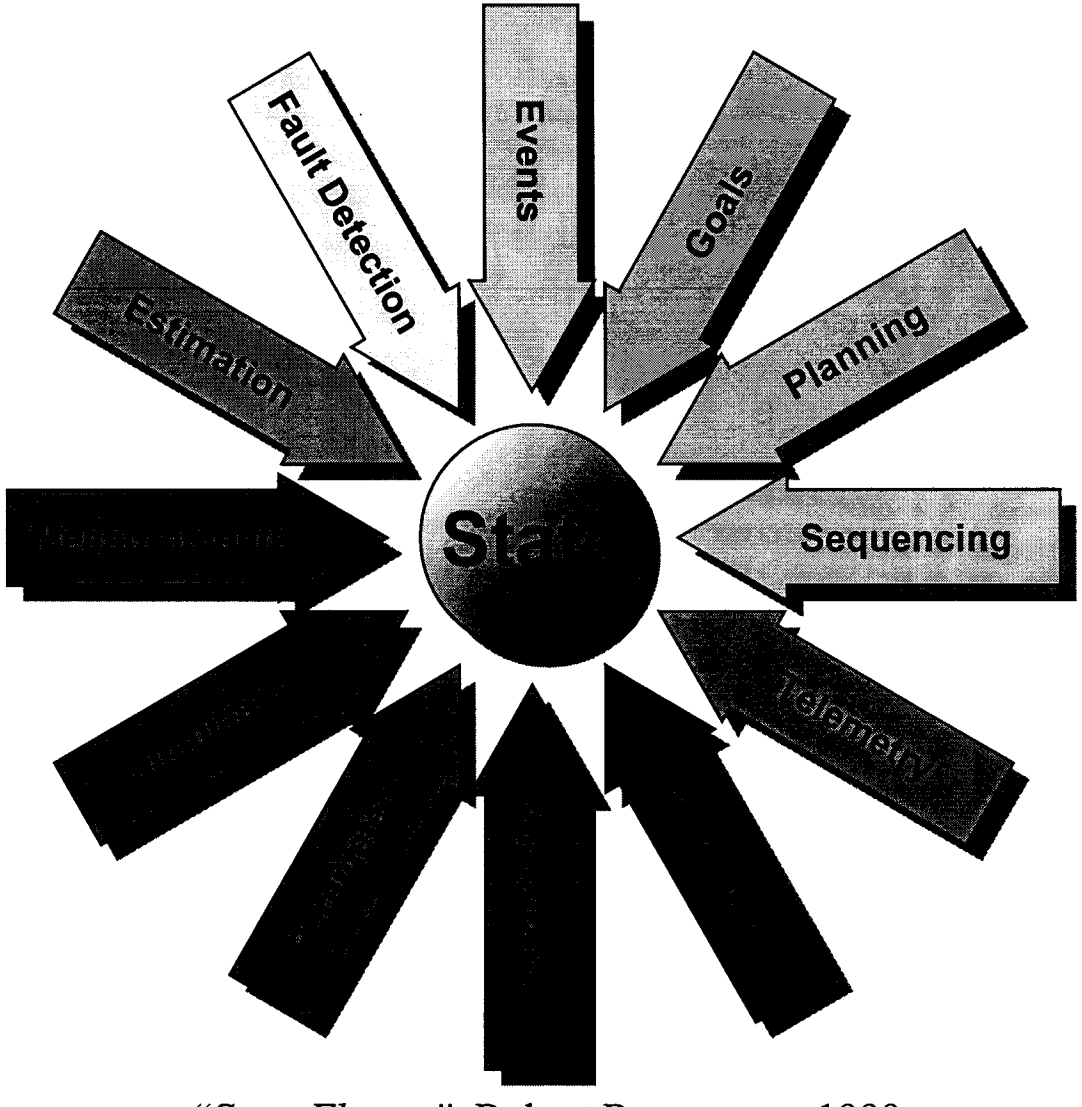


State is Central

All application-level functions of the MDS architecture involve the concept of state

- The **state** of a system at some time is a snapshot of all the "interesting" changeable features of the system
- A system **model** describes all the "interesting" features of how a system changes
- The **system** includes the spacecraft, its environment, and other actors in the environment (e.g. ground stations) with which it interacts in an "interesting" way

The essence of the MDS state-based architecture is to place the explicit management of state at the center of all system activities

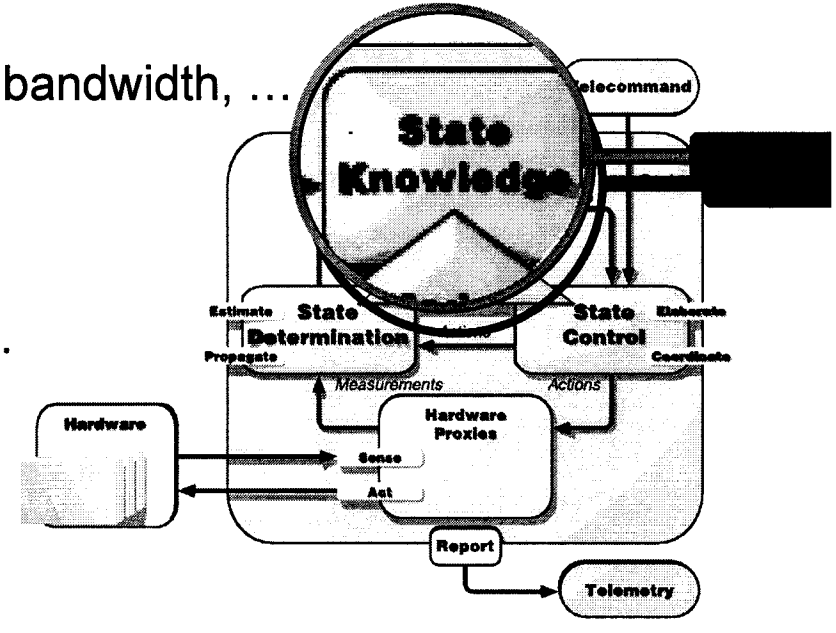


"State Flower", Robert Rasmussen, 1999.

State Knowledge
Everything You Need to Know

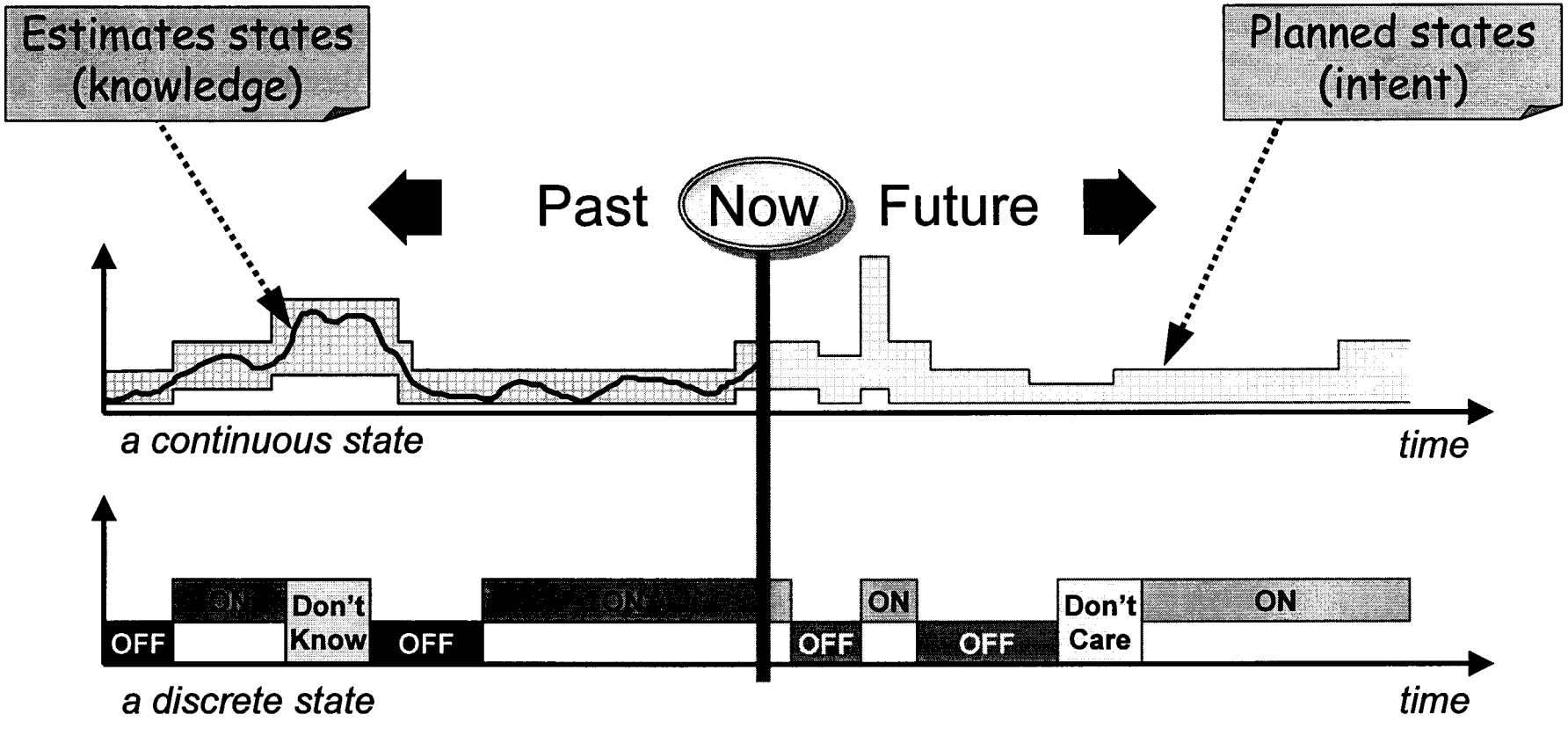
- Dynamics
  - Vehicle position & attitude, gimbal angles, wheel rotation, …
- Environment
  - Ephemeris, light level, atmospheric profiles, terrain, …
- Device status
  - Configuration, temperature, operating modes, failure modes, …
- Parameters
  - Mass properties, scale factors, biases, alignments, noise levels, …
- Resources
  - Power & energy, propellant, data storage, bandwidth, …
- Data product collections
  - Science data, measurement sets, …
- Data management & transport policies
  - Compression/deletion, transport priority, …
- Externally controlled factors
  - Space link schedule & configuration, …

… and so on



State Timelines

- **State timelines** maintain the value or set of possible values (e.g., a range) of a state variable as a function of time
- They capture both knowledge and intent about state

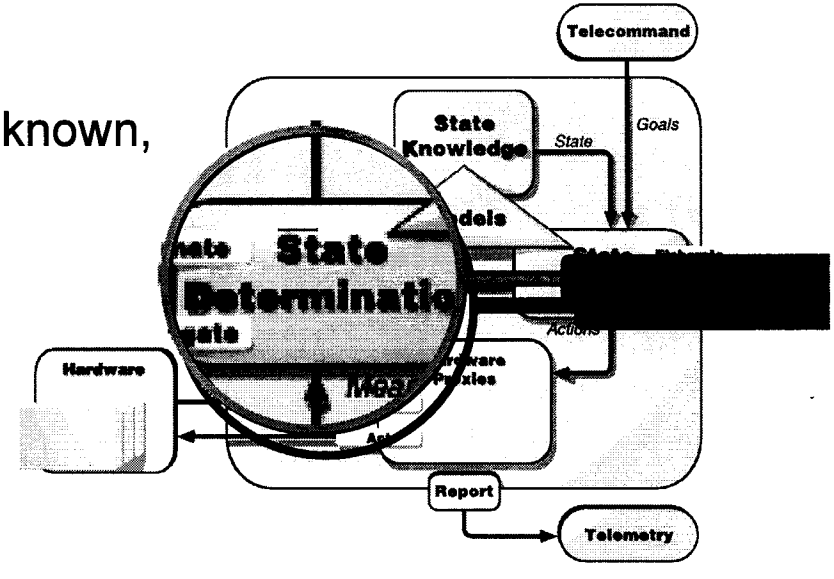


State Determination

Making Sense of the World

- One can act only on one's **knowledge** of the system
  - Knowledge is **what** you know, **not how** you know it
  - Observations (e.g., measurements) are *not* knowledge
- **Estimators** find "good" explanations for observations and other evidence, given a **model** of how things work
  - Knowledge may be **propagated** into the future, given models and plans

- All knowledge is **uncertain**
  - Judgment must be based both on what is known, and on how well it is known
- However, one *can* **achieve** local consistency of knowledge



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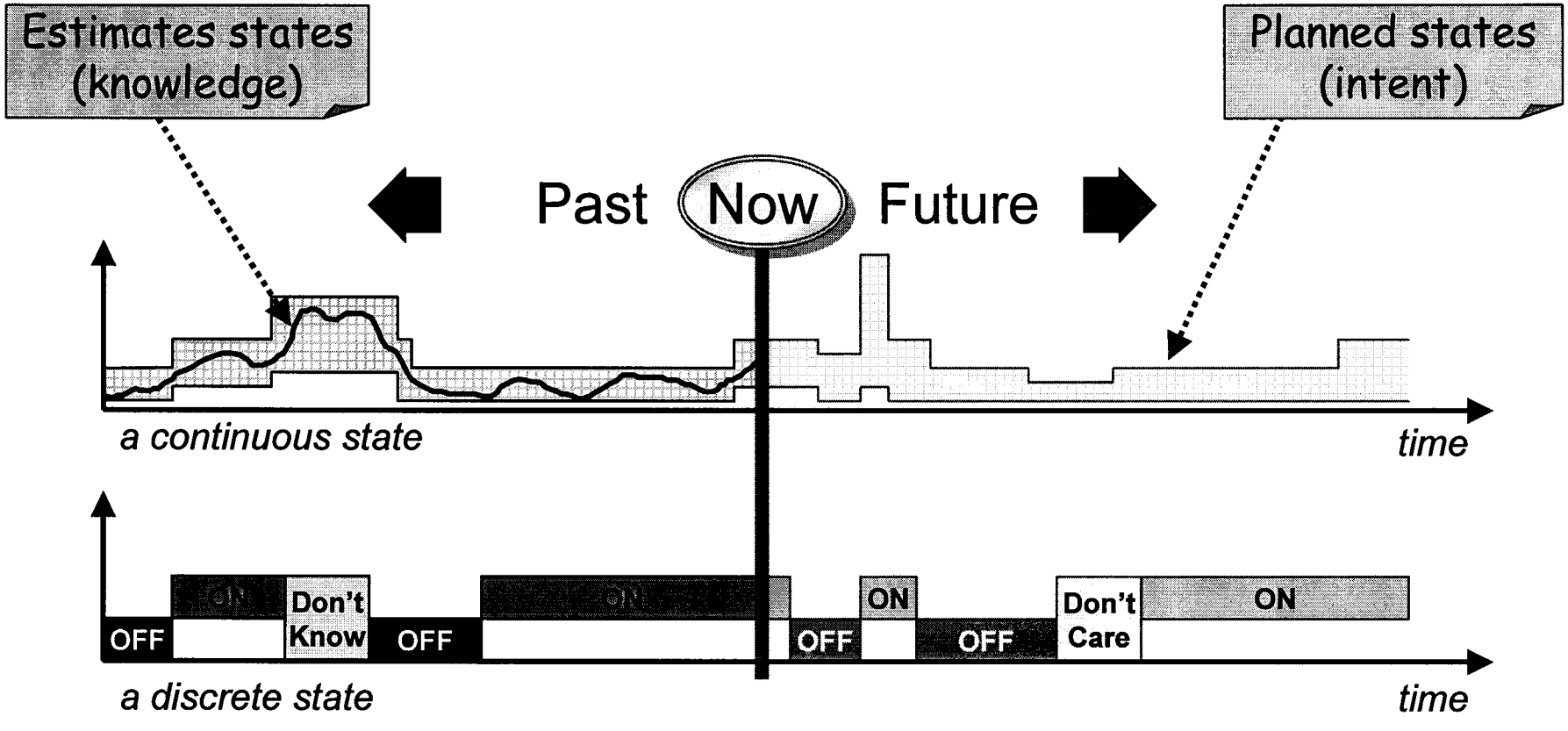
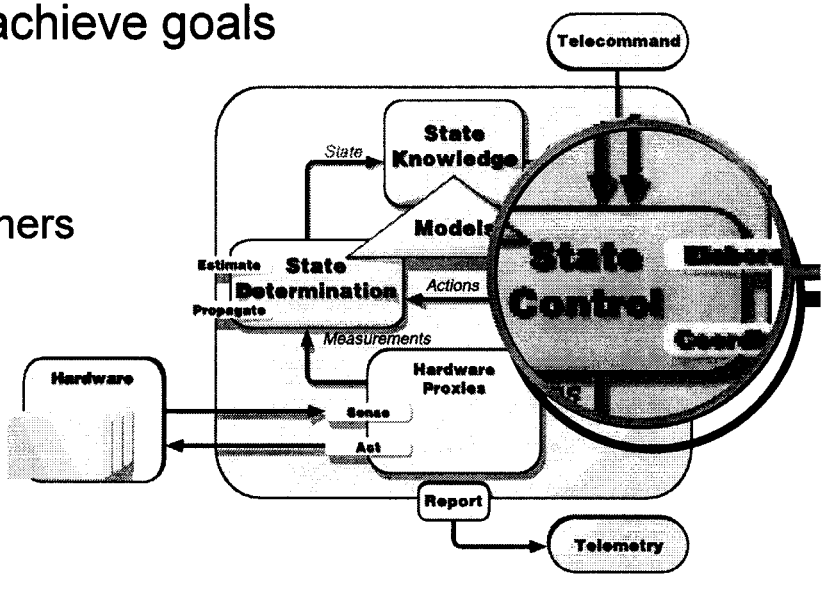


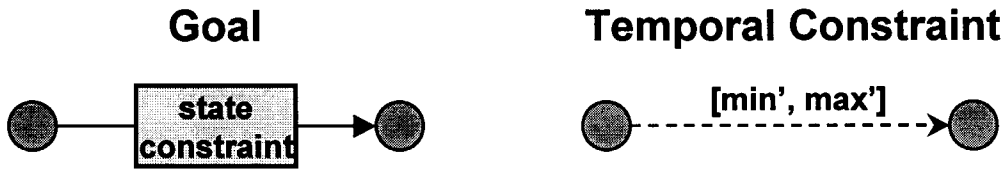
State Control
Closing the Loop

- Operators express their intent in the form of **goals**
  - Goals declare **what** should happen, **not how**
  - Goals specify constraints on state and constraints on time
- High level goals are elaborated recursively into lower level goals
  - **Elaboration** may be conditional, in order to react to present circumstances
  - **Coordination** of activities is accomplished by **scheduling**
  - Conflicts are resolved, with priority as final arbiter
- Knowledge of all states is maintained, as required to achieve goals
  - Knowledge is compared to goal constraints to test for compliance
- Corrective action is applied, as required to achieve goals
  - Alternate methods of **achievement** may be applied at any level
  - Unachievable goals (and their elaborations) are dropped individually without sacrificing others
- **Supports fault tolerance, critical activities, *in situ* autonomy, opportunistic science, and more**

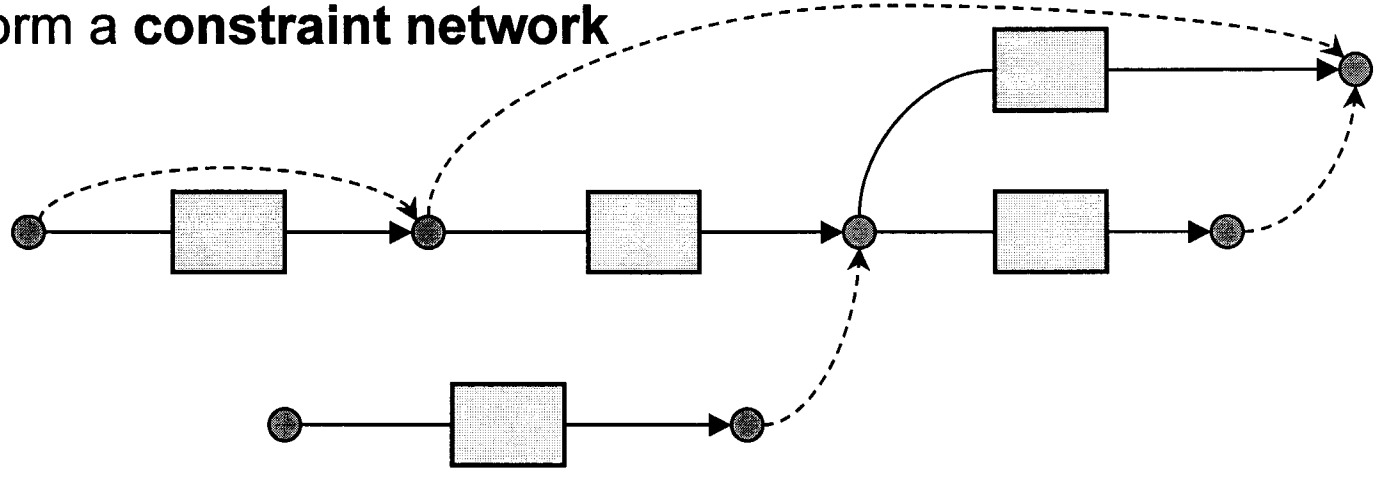


Constraint Networks

- Goals and temporal constraints each connect a pair of time points

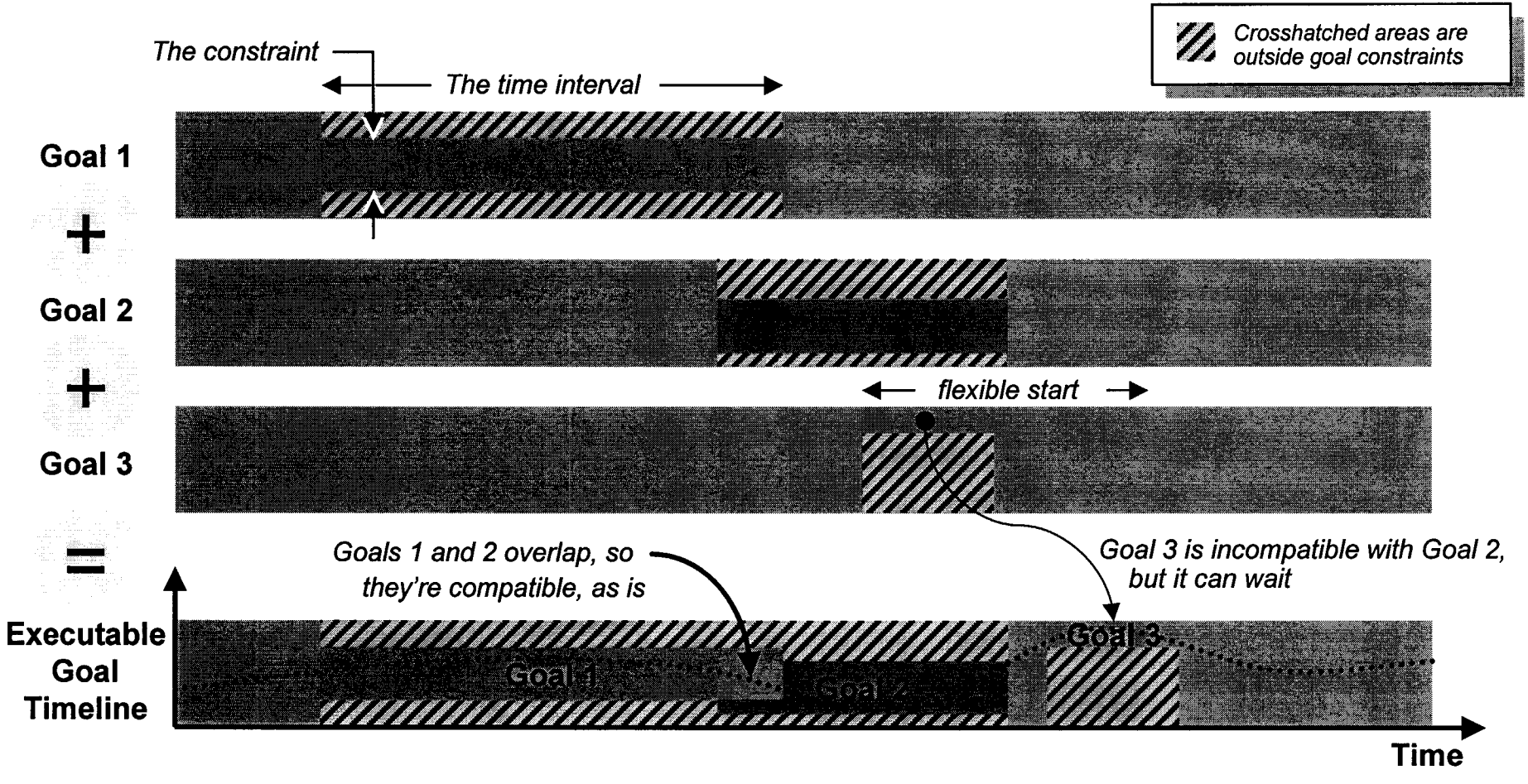


- Time points are often shared (e.g., one beginning as another ends)
- A collection of connected goals and temporal constraints form a **constraint network**



Resolving Conflicts

- Example: three goals on the same state



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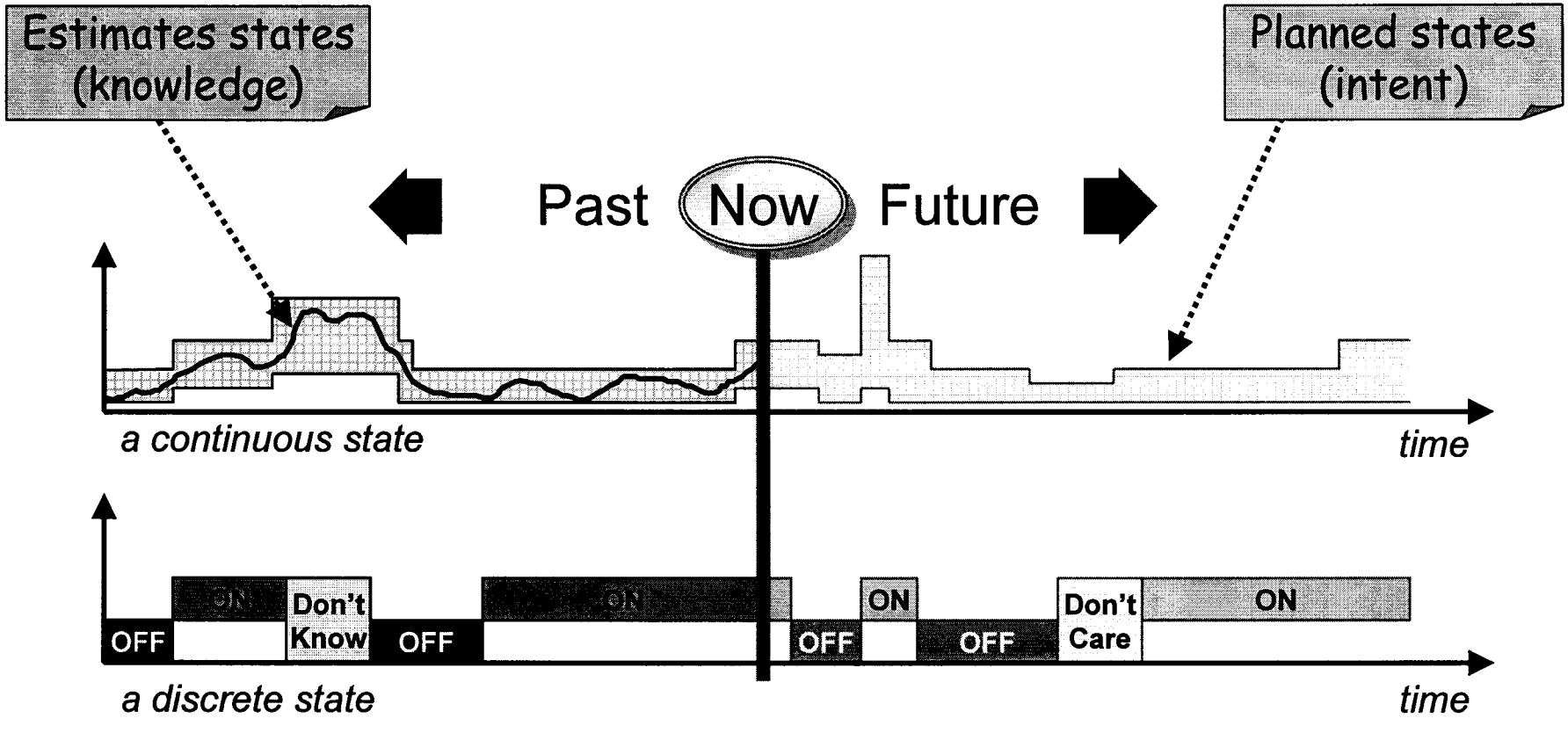
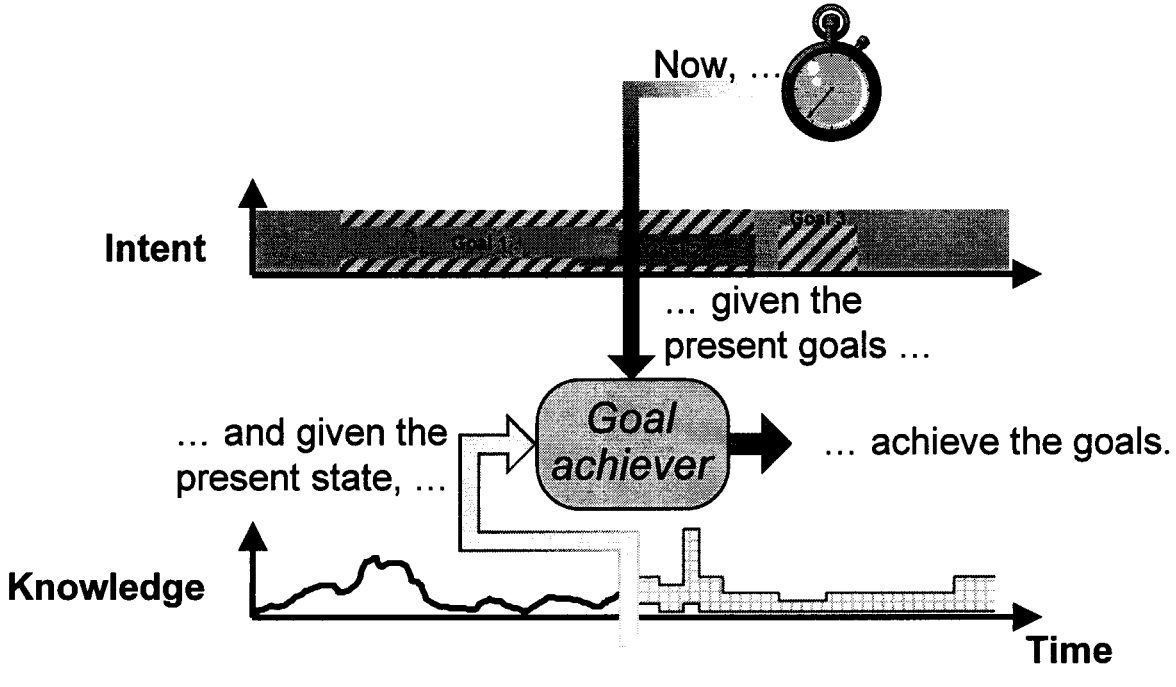


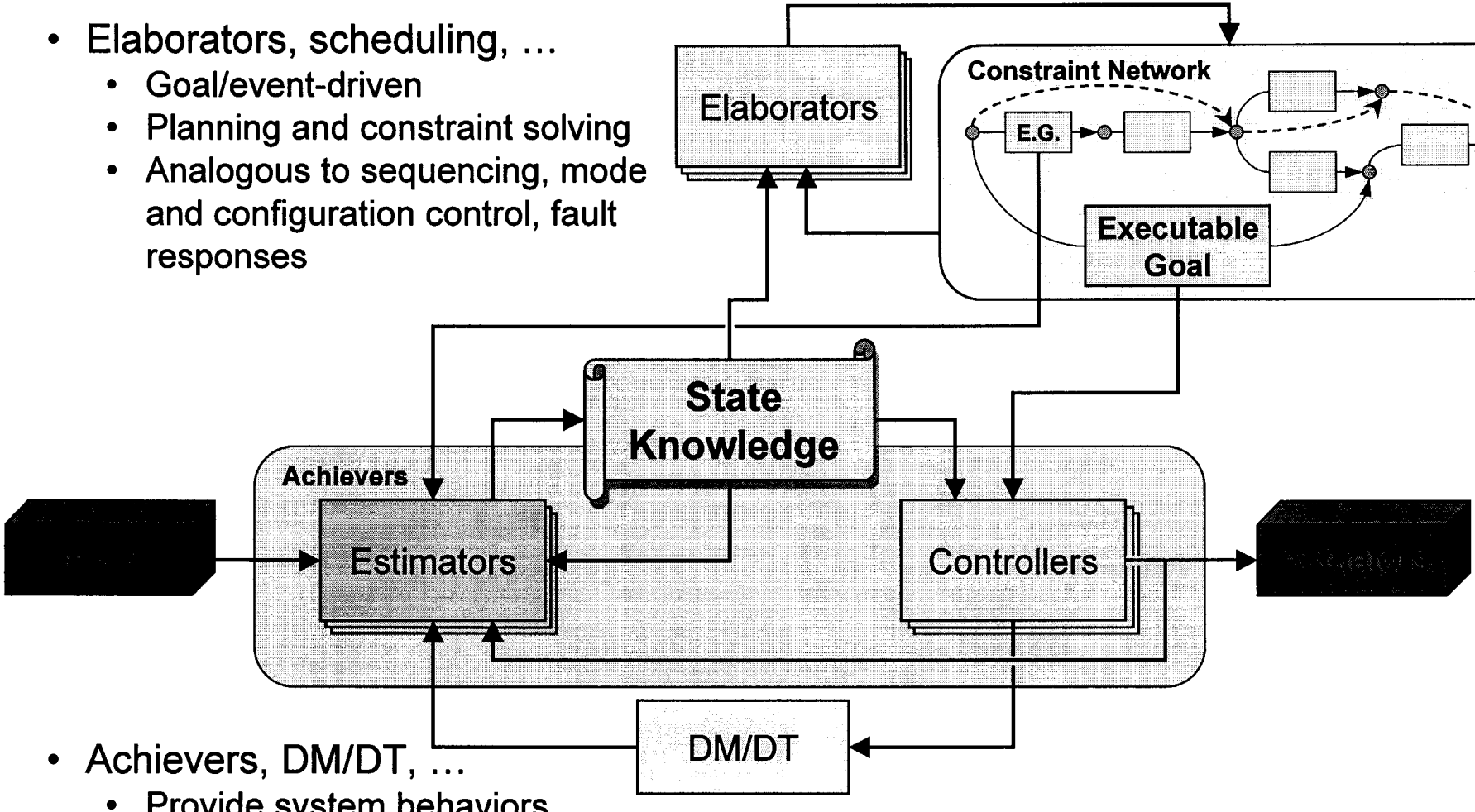
Timeline Execution

- Goals are accepted if successfully placed on the timeline for the goal state variable
- Goals are frozen and acted upon when they appear on the timeline in the immediate future
- Goals are acted upon by **achievers** assigned to each state variable
- Elaborators monitor execution and adapt plans, as necessary



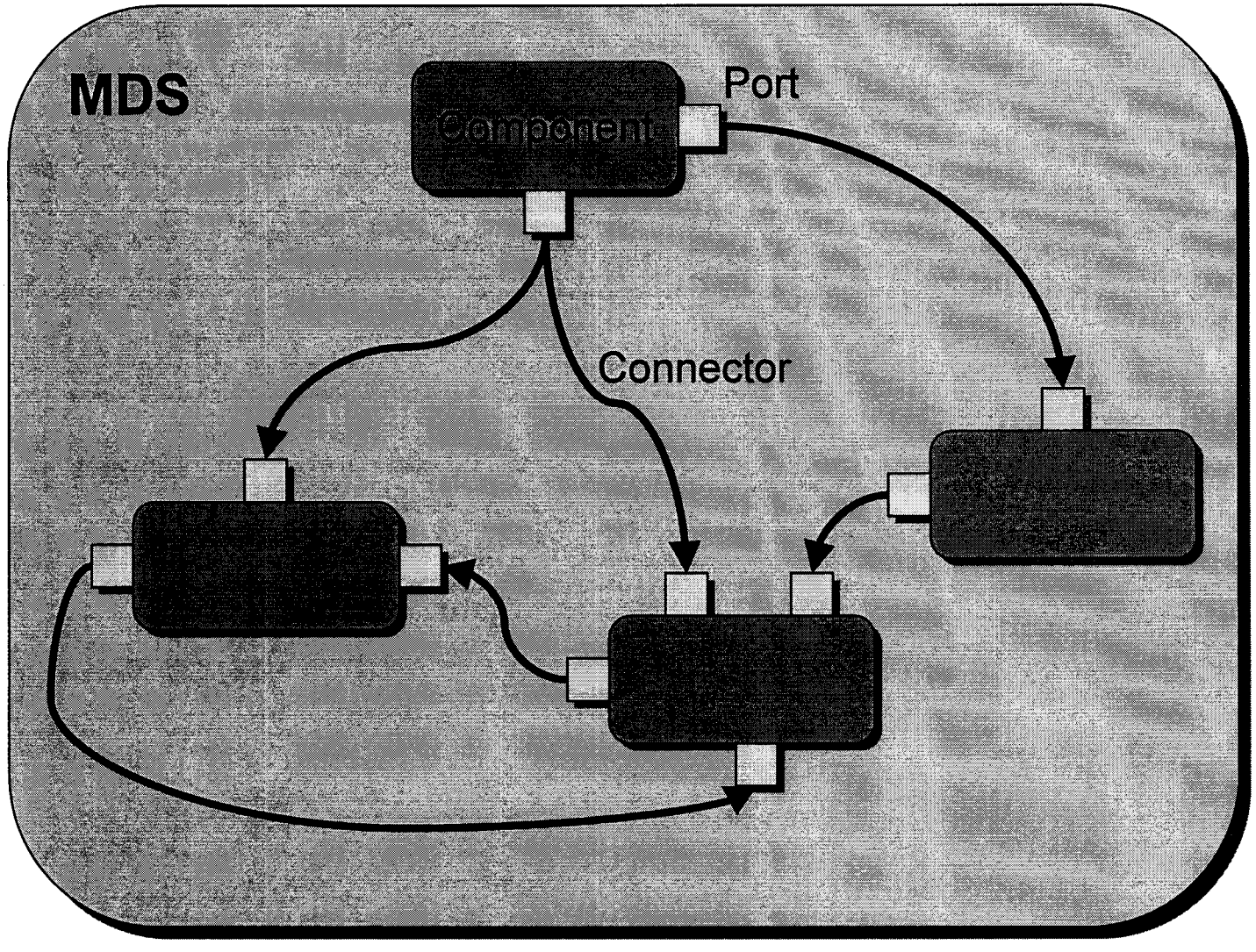
Putting It Together

- Elaborators, scheduling, …
  - Goal/event-driven
  - Planning and constraint solving
  - Analogous to sequencing, mode and configuration control, fault responses



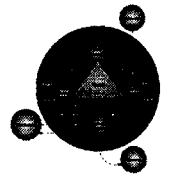
- Achievers, DM/DT, …
  - Provide system behaviors
  - Managed via goals and temporal constraints
  - Fairly conventional real-time monitoring and control processes

Component-Based Architecture



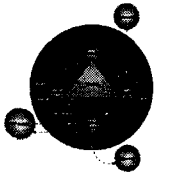
- First class types and instances
  - Components, connectors, interfaces
- Explicit interface ports
  - Describe semantics of interface use
- Type safety
- Role safety

Benefits: Development & Testing



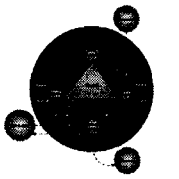
- Complex interactions understood at mission, system and component levels
- State decomposition facilitates tracking of system scalability
- Domain knowledge expressed explicitly as models
- Component architecture facilitates measures of responsiveness
- Architecture requires state be determined honestly from the evidence
- Architecture provides a mechanism for identifying the range and impact of faults
- Architecture authorizes and monitors all resource usage
- Uniform architecture facilitates cost tracking associated with system complexity and system reconfiguration.
- Cost models based on objective development data facilitate estimation of fault-related development.

Benefits: Safer Software



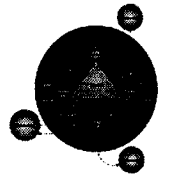
- Initialization/finalization dependencies explicitly represented
  - Dependency order enforced
  - Automatic detection of circular dependencies
- Software interfaces and interactions elevated to first-class design elements
  - Eliminates 'hidden' interactions that cause hard-to-find problems
- Component approach facilitates use of advanced verification techniques
  - Detect synchronization errors that cause deadlocks and data races
- Run-time component manager enforces architectural rules regarding instantiation of components and valid connections

Benefits: Verification by Design



- Goals specify explicit constraints on state and time that are continually monitored, so deviations from expected behavior are immediately reported.
- Errors in units of measurement detected through SI units package
- Component manager enforces architectural rules about legal connections
- The initialization/finalization package reports circular dependencies and improperly held resources
- Unified state architecture supports direct comparison between simulated state and estimated state
- Separation of models from reusable algorithms makes validation of mission-specific items simpler
- 'Smart pointers' eliminate problems of memory leaks and dangling pointers

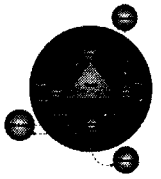
Benefits: Mission Operations

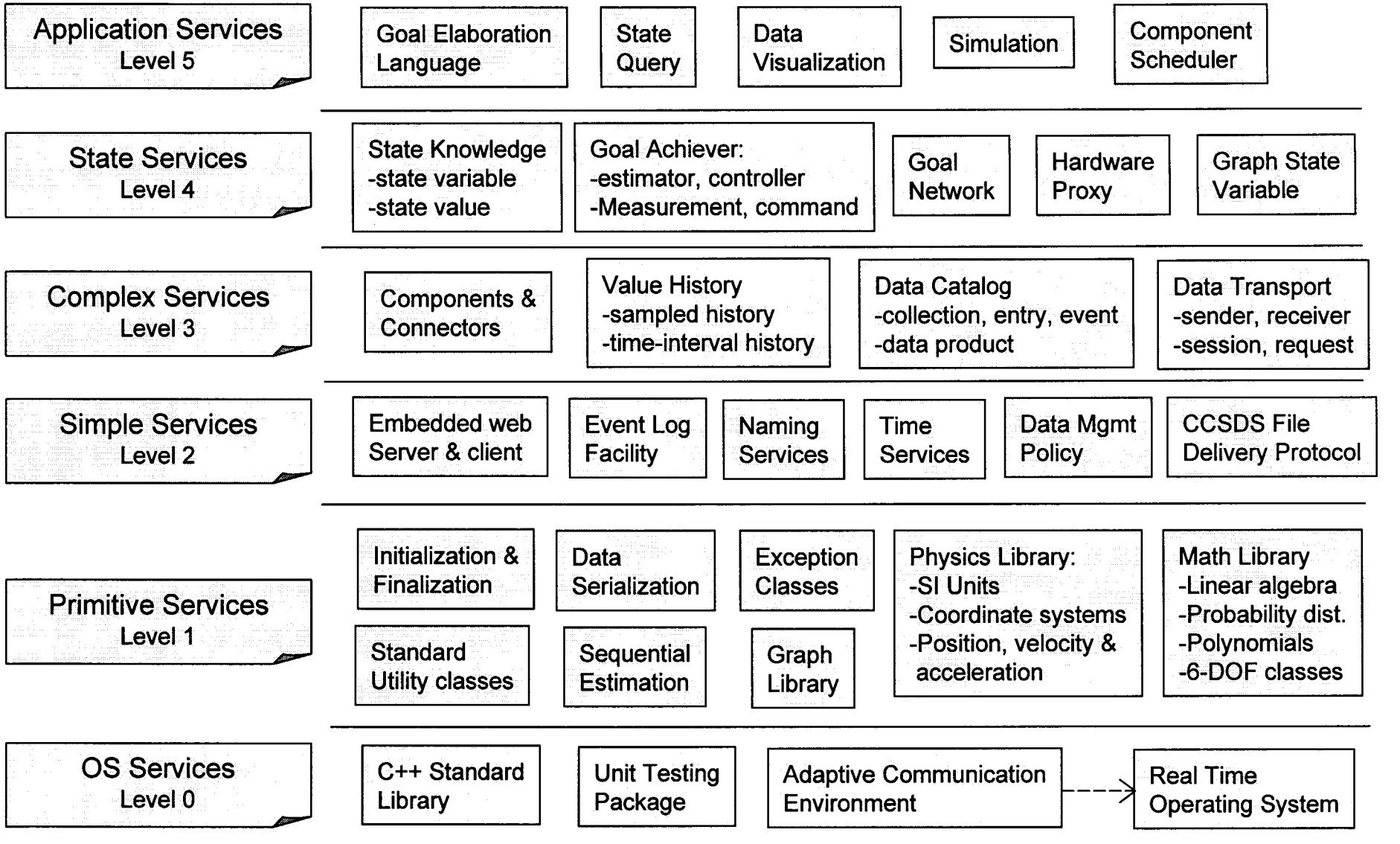


- Operation based on *what* (constraints on state) rather than *how* (command sequences)
- Operators can migrate capability and responsibility from ground to flight system to simplify operations and reduce communication needs
- Models express key functional relations among system states, command effects, and observed measurements
- Disciplined architecture provides uniform fault-metric mechanisms
- Fault sources are explicitly captured in goal-failure trees
- Fault response is explicitly modeled as goal elaborations
- Uniform data collection mechanism facilitates run-time monitoring and metrics associated with adaptivity and diagnosability

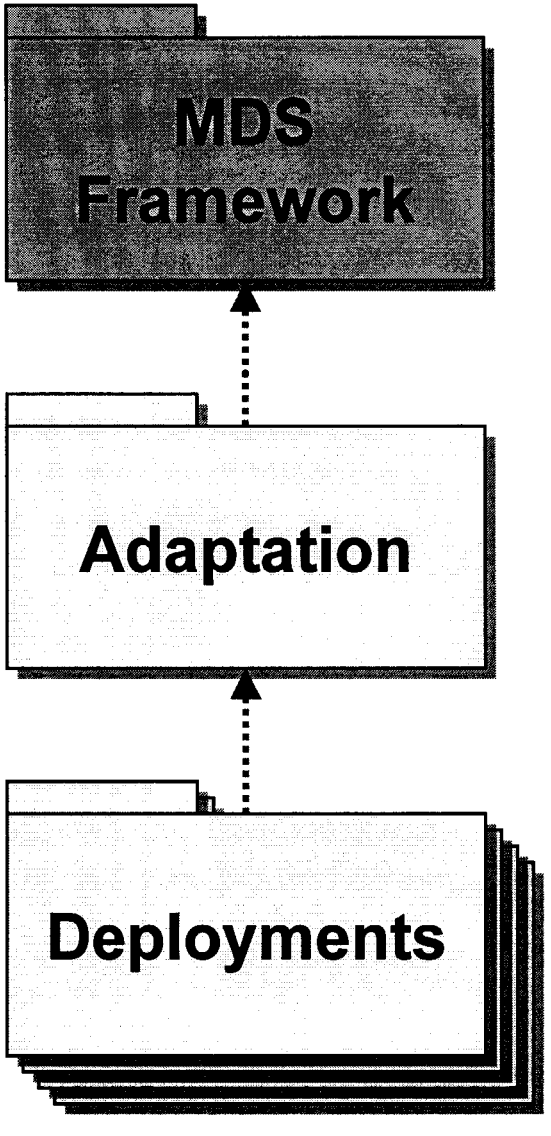
MDS Framework Packages

Each requirements is generally levied on a particular package



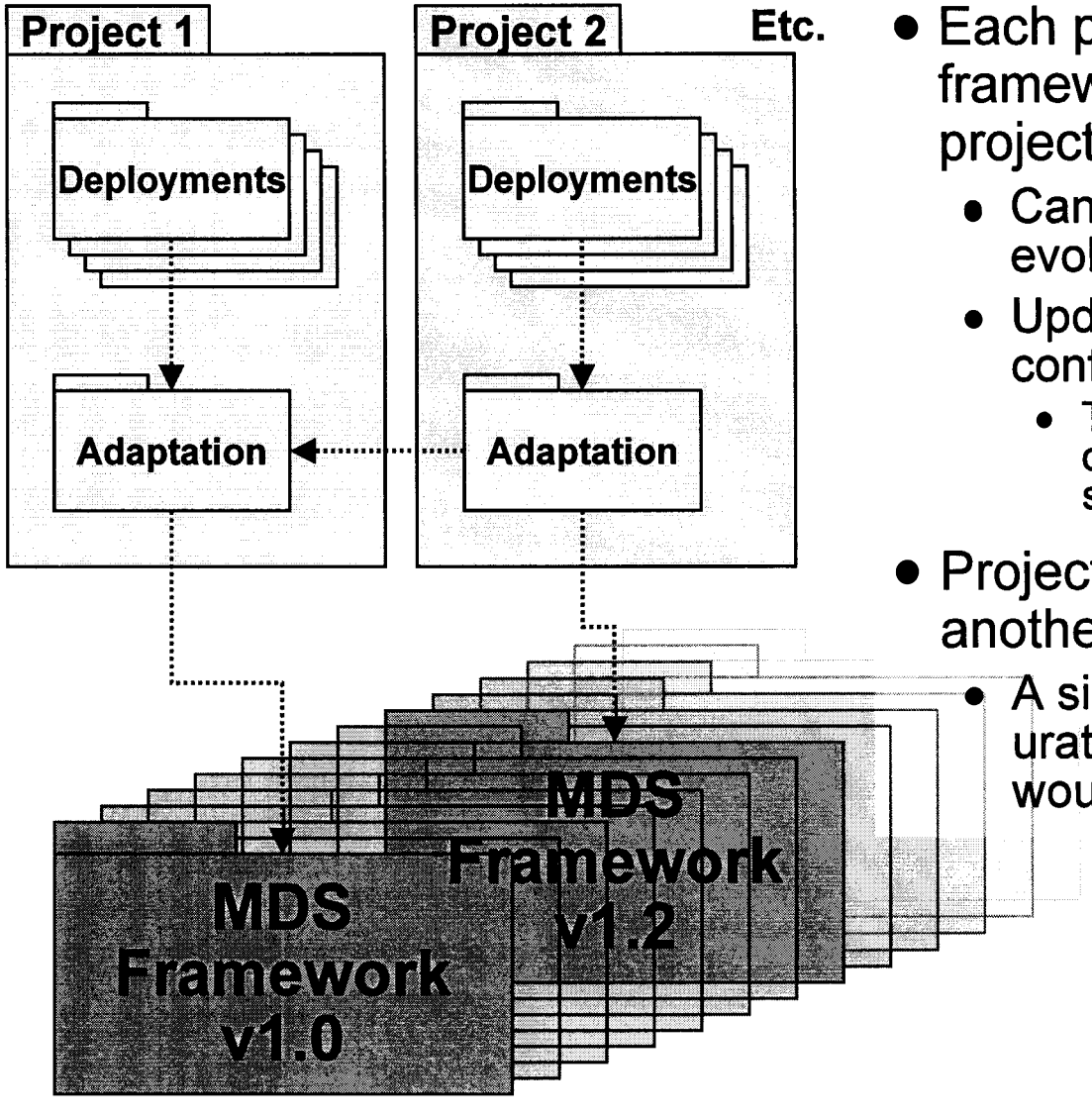


The MDS Common Model



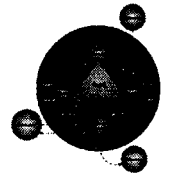
- The **MDS Framework** is the collection of most core classes within the MDS architecture
  - Developed and maintained exclusively by MDS
  - Uniform (except for versioning) across MDS adaptations
- Each project does an **Adaptation** of the framework
  - Captures project requirements and scenarios
  - Extends framework classes to address functions and configurations specific to the project
  - Reusable extensions are generalized (if necessary) and moved to the framework
- Several **Deployments** of the adaptation are defined
  - These are the executable configurations to be used in various settings (test beds, flight, ground, etc.)

Reuse Among Projects



- Each project uses the same framework, except that later projects will adapt later versions
  - Can continue to track framework evolution up to some freeze point
  - Updates to frozen version are confined to that project
    - Though mainline framework development may decide to make some of the same updates
- Projects can adapt from one another
  - A similar track-then-freeze configuration management process would be necessary

Summary



- MDS addresses…
  - Architectures for both functional and software design interactions
  - Unification and reuse across deployments and projects
  - A wide range of technical issues from autonomous control to data management
  - The collaboration of systems and software engineering
  - Processes, tools, and design rigor up to the challenge of a flight program

- State and Component Architectures are the bedrock of our approach
  - Each exploits a relatively small but powerful set of ideas
  - The two architectures complement one another in a natural but far-reaching manner

End