Information-Driven Science in Pervasive Grid Environments

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(Ack: NSF, DoE, NIH)
Outline

• Pervasive Grid Environments - Unprecedented Opportunities

• Pervasive Grid Environments - Unprecedented Challenges, Opportunities

• Project AutoMate @ TASSL, Rutgers University – Enabling Autonomic Applications in Pervasive Grid Environments

• An Illustrative Application

• Concluding Remarks
Pervasive Grid Environments - Unprecedented Opportunities

- **Pervasive Grids Environments**
  - Seamless, secure, on-demand access to and aggregation of, geographically distributed computing, communication and information resources
    - Computers, networks, data archives, instruments, observatories, experiments, sensors/actuators, ambient information, etc.
  - Context, content, capability, capacity awareness
  - Ubiquity and mobility

- **Knowledge-based, information/data-driven, context/content-aware computationally intensive science**
  - Symbiotically and opportunistically combine computations, experiments, observations, and real-time information to model, manage, control, adapt, optimize, …
    - Crisis management, monitor and predict natural phenomenon, monitor and manage engineering systems, optimize business processes

- **A new paradigm for scientific investigation?**
  - Seamless access
    - resources, services, data, information, expertise, …
  - Seamless aggregation
  - Seamless (opportunistic) interactions/couplings
The original Grid concept has moved on!

- Coordinated resource sharing and problem solving in dynamic, multi-institutional virtual organizations.

Source: I. Foster et al
Pervasive Grid Environments and Information Driven Science

Experts interact and collaborate using ubiquitous and pervasive portals.

Experts query, configure resources.

Experts mine archive, match real-time data with history.

Experts monitor/interact with/interrogate/steer models (“what if” scenarios,…). Application notifies experts of interesting phenomenon.

Models write into the archive.


Real-time data assimilation/injection (sensors, instruments, experiments, data archives).

Automated mining & matching.

Resources discovered, negotiated, co-allocated on-the-fly. Model/Simulation deployed.

Applications & Services

Computers, Storage, Instruments, ...

Data Archive & Sensors

Scientists

Scientists

Laptop

Computer

PDA

Resouces
discovered,
negotiated, co-allocated on-the-fly. Model/Simulation deployed.

Resources

Data Archives

Sensors, Non-Traditional Data Sources

Experts

Applications & Services

Model A

Model B
Information-driven Management of Subsurface Geosystems: The Instrumented Oil Field (with UT-CSM, UT-IG, OSU, UMD, ANL)

Detect and track changes in data during production.
Invert data for reservoir properties.
Detect and track reservoir changes.
Assimilate data & reservoir properties into the evolving reservoir model.
Use simulation and optimization to guide future production.
Dynamic Decision System

Optimize
- Economic revenue
- Environmental hazard
- ...
Based on the present subsurface knowledge and numerical model

Update knowledge of model

Improve numerical model

Dynamic Data-Driven Assimilation

Improve knowledge of subsurface to reduce uncertainty

Acquire remote sensing data

Plan optimal data acquisition

Subsurface characterization

Experimental design

Data assimilation

START
Vision: Diverse Geosystems – Similar Solutions

Landfills

Oilfields

Underground Pollution

Undersea Reservoirs

Models

Simulation

Control

Data
Management of the Ruby Gulch Waste Repository (with UT-CSM, INL, OU)

- Ruby Gulch Waste Repository/Gilt Edge Mine, South Dakota
  - ~ 20 million cubic yard of waste rock
  - AMD (acid mine drainage) impacting drinking water supplies

- Monitoring System
  - Multi electrode resistivity system (523)
    - One data point every 2.4 seconds from any 4 electrodes
  - Temperature & Moisture sensors in four wells
    - Flowmeter at bottom of dump
    - Weather-station
    - Manually sampled chemical/air ports in wells
    - Approx 40K measurements/day

Dynamic Data-Driven Waste Management

Observations

Sensors

Data Assimilation

Models, Surrogate/Reduced models

Optimization Algorithms

Ruby Gulch Waste Repository

Actuators

Controllable input

Control algorithms

Optimization
Adaptive Fusion of Stochastic Information for Imaging Fractured Vadose Zones (with U of AZ, OSU, U of IW)

• Near-Real Time Monitoring, Characterization and Prediction of Flow Through Fractured Rocks
Data-Driven Forest Fire Simulation (U of AZ)

- Predict the behavior and spread of wildfires (intensity, propagation speed and direction, modes of spread)
  - based on both dynamic and static environmental and vegetation conditions
  - factors include fuel characteristics and configurations, chemical reactions, balances between different modes of heat transfer, topography, and fire/atmosphere interactions.

System for Laser Treatment of Cancer – UT, Austin

Source: L. Demkowicz, UT Austin
Integrated Wireless Phone Based Emergency Response System – Notre Dame

- Detect abnormal patterns in mobile call activity and locations
- Initiate dynamic data driven simulations to predict the evolution of the abnormality
- Initiate higher resolution data collection in localities of interest
- Interface with emergency response Decision Support Systems

Source: G. Madey, ND
Many Application Areas ….

- Hazard prevention, mitigation and response
  - *Earthquakes, hurricanes, tornados, wild fires, floods, landslides, tsunamis, terrorist attacks*
- Critical infrastructure systems
  - *Condition monitoring and prediction of future capability*
- Transportation of humans and goods
  - *Safe, speedy, and cost effective transportation networks and vehicles (air, ground, space)*
- Energy and environment
  - *Safe and efficient power grids, safe and efficient operation of regional collections of buildings*
- Health
  - *Reliable and cost effective health care systems with improved outcomes*
- Enterprise-wide decision making
  - *Coordination of dynamic distributed decisions for supply chains under uncertainty*
- Next generation communication systems
  - *Reliable wireless networks for homes and businesses*

*Source: M. Rotea, NSF*
Outline

• Pervasive Grid Environments - Unprecedented Opportunities

• Pervasive Grid Environments - Unprecedented Challenges
  – Uncertainty
    • System uncertainty
    • Application uncertainty
    • Information uncertainty

• Project AutoMate @ TASSL, Rutgers University – Enabling Autonomic Applications in Pervasive Grid Environments

• An Illustrative Application

• Concluding Remarks
Pervasive Grid Applications – Unprecedented Challenges: Uncertainty

• System Uncertainty
  – Very large scales
  – Ad hoc (amorphous) structures/behaviors
    • p2p, hierarchical, etc, architectures
  – Dynamic
    • entities join, leave, move, change behavior
  – Heterogeneous
    • capability, connectivity, reliability, guarantees, QoS
  – Lack of guarantees
    • components, communication
  – Lack of common/complete knowledge
    • number, type, location, availability, connectivity, protocols, semantics, etc.
Pervasive Grid Applications – Unprecedented Challenges: Uncertainty

• Application Uncertainty
  – *Dynamic behaviors*
    • *space-time adaptivity*
  – *Dynamic and complex couplings*
    • *multi-physics, multi-model, multi-resolution, ....*
  – *Dynamic and complex (ad hoc, opportunistic) interactions*
    • *application ↔ application, application ↔ resource, application ↔ data, application ↔ user, ...*
  – *Software/systems engineering issues*
    • *Emergent rather than by design*

• Information Uncertainty
  – *Availability, resolution, quality of information*
  – *Devices capability, operation, calibration*
  – *Trust in data, data models*
Pervasive Grid Applications – Research Issues, Opportunities

- Applications and algorithms
  - **robust model/algorithm development and calibration**
    - *impact of information on models and models on information acquisition*
  - **continuous model, algorithm, emergent system validation**
  - **uncertainty estimation**
  - **parameter selection and optimization**
  - **observability, identifiability, tractability**

- Measurement and actuation systems
  - "**real-time**" data collection and transport
    - *in-network aggregation, assimilation*
  - **data selection and application integration, data quality management**
  - **data/data-model heterogeneity**
  - **security trust, data provenance, audit trails**
  - **actuation and control**
Pervasive Grid Applications – Research Issues, Opportunities

• Systems software
  – *programming systems/models for data integration and runtime self-management*
    • *components and compositions capable of adapting behavior and interactions*
    • *correctness, consistency, performance, quality-of-service constraints*
  – *data management mechanisms for acquisition with real time, space and data quality constraints*
    • *high data volumes/rates, heterogeneous data qualities, sources*
  – *runtime execution services that guarantee correct, reliable execution with predictable and controllable response time*
    • *data assimilation, injection, adaptation*
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Programming Pervasive Grid Systems

- Programming System
  - programming model, languages/abstraction – syntax + semantics
    - entities, operations, rules of composition, models of coordination/communication
  - abstract machine, execution context and assumptions
  - infrastructure, middleware and runtime

- Hide or expose uncertainty?
  - robustness, ease of programming
  - the inverted stack …

• Computing has evolved and matured to provide specialized solutions to satisfy relatively narrow and well defined requirements in isolation
  – performance, security, dependability, reliability, availability, throughput, pervasive/amorphous, automation, reasoning, etc.

• In case of pervasive Grid applications/environments, requirements, objectives, execution contexts are dynamic and not known a priori
  – requirements, objectives and choice of specific solutions (algorithms, behaviors, interactions, etc.) depend on runtime state, context, and content
  – applications should be aware of changing requirements and executions contexts and to respond to these changes are runtime

• Autonomic computing - systems/applications that self-manage
  – use appropriate solutions based on current state/context/content and based on specified policies
  – address uncertainty at multiple levels
  – asynchronous algorithms, decoupled interactions/cooperation, content-based substrates
Project AutoMate: Enabling Autonomic Applications

- Conceptual models and implementation architectures
  - Programming systems based on popular programming models
    - object, component and service based prototypes
  - content-based coordination and messaging middleware
  - amorphous and emergent overlays
- http://automate.rutgers.edu
Project AutoMate: Components

- Accord – A Programming System for Autonomic Grid Applications
- Rudder/Comet – Decentralized Coordination Middleware
- Meteor – Content-based Interactions Middleware
- ACE – Autonomic Composition Engine
- Squid – Decentralized Information Discovery and Content-based Routing
- SESAME – Context-Aware Access Management
- DAIS – Cooperative Protection against Network Attacks

More information/Papers – [http://automate.rutgers.edu](http://automate.rutgers.edu)

Accord: Rule-Based Programming System

• Accord is a programming system which supports the development of autonomic applications.
  – Enables definition of autonomic components with programmable behaviors and interactions.
  – Enables runtime composition and autonomic management of these components using dynamically defined rules.
    • *Dynamic specification of adaptation behaviors using rules.*
    • *Enforcement of adaptation behaviors by invoking sensors and actuators.*
    • *Runtime conflict detection and resolution.*

• 3 Prototypes: Object-based, Components-based (CCA), Service-based (Web Service)

Autonomic Element in Accord

Element Manager

Computational Element

- Functional Port
- Control Port
- Operational Port

Autonomic Element

Event generation
Other Interface invocation
Actuator invocation

Internal state
Rules
Contextual state
The Accord Runtime Infrastructure

Application workflow

Application strategies
Application requirements

Composition manager

Interaction rules
Behavior rules

Interaction rules
Behavior rules

Interaction rules
Behavior rules

Interaction rules
Behavior rules
Element/Service Managers are augmented with LLC Controllers

- monitors state/execution context of elements
- enforces adaptation actions determined by the controller
- augment human defined rules
Decentralized (Decoupled/Asynchronous) Content-based Middleware Services
SquidTON: Reliability and Fault Tolerance

- Pervasive Grid systems are dynamic, with nodes joining, leaving and failing relatively often
  - => data loss and temporarily inconsistent overlay structure
  - => the system cannot offer guarantees
    - Build redundancy into the overlay network
    - Replicate the data
- SquidTON = Squid Two-tier Overlay Network
  - Consecutive nodes form unstructured groups, and at the same time are connected by a global structured overlay (e.g. Chord)
  - Data is replicated in the group
**Content Descriptors and Information Space**

- Data element = a piece of information that is indexed and discovered
  - *Data, documents, resources, services, metadata, messages, events, etc.*
- Each data element has a set of keywords associated with it, which describe its content => data elements form a keyword space

2D keyword space for a P2P file sharing system

3D keyword space for resource sharing, using the attributes: storage space, base bandwidth and cost

Complex query (comp*, *)

Complex query (10, 20-25, *)
Content Indexing: Hilbert SFC

- \( f: \mathbb{N}^d \rightarrow \mathbb{N} \), recursive generation

- **Properties:**
  - Digital causality
  - Locality preserving
  - Clustering

*Cluster*: group of cells connected by a segment of the curve
Content Routing/Discovery - Squid

Query: (Storage space = 30, Bandwidth = *) => Binary query (011110, *)
Query Engine – Experimental Evaluation

- System size: 103 to 106 nodes
- Data:
  - Uniformly distributed, synthetic generated data
  - 4*10^5 CiteSeer data
- Load balanced system

- Experiments:
  - Number of clusters generated for a query
  - Number of nodes queried
- All results are plotted on a logarithmic scale
Squid Content Routing/Discovery Engine: Optimization

- Number of clusters generated for queries with coverage 1%, 0.1%, 0.01%, with and without optimization.
- The results are normalized against the clusters that the query defines on the curve (i.e. without optimization).

### Graphs

**3D Uniformly distributed data**

- Normalized number of clusters vs. system size.
- Lines represent different query coverages: 1%, 0.1%, 0.01%.

**3D CiteSeer data**

- Normalized number of clusters vs. system size.
- Lines represent different query coverages: 1%, 0.1%, 0.01%.
Squid Content Routing/Discovery Engine – Nodes Queried

- Percentage of nodes queried for queries with coverage 1%, 0.1%, 0.01%, with and without optimization

3D Uniformly distributed data

3D CiteSeer data
Semantics of Associative Rendezvous Interactions

- **Messages**
  - \((header, action, data)\)
  - Symmetric post primitive: does not differentiating between interest/data

- **Associative selection**
  - match between interest and data profiles

- **Reactive behavior**
  - Execute action field upon matching

Profile = list of (attribute, value) pairs:
Example:
\(<(sensor\_type, temperature), (latitude, 10), (longitude, 20)>\)

\[
\text{post} (<p_1, p_2>, \text{store}, \text{data}) \\
\text{notify\_data}(C2) \\
\text{post}(<p_1, *>, \text{notify\_data}(C2)) \\
\]
Comet Coordination Space

- A virtual global shared-space is constructed from a semantic multi-dimensional information space, which is deterministically mapped onto the system peer nodes.
- The space is associatively accessible by all system peer nodes. Access is independent of the physical locations of tuples or hosts.
  - **Tuple distribution**
    - A tuple/template is associated with k keywords
    - *Squid* content-based routing engine used or exact and approximate tuple distribution and retrieval
  - **Transient spaces**
    - Enable application to explicitly exploit context locality

Coordination primitives

- **Basic primitives**
  - Out, In, Rd

- **Tuple retrieval**
  - **Exact retrieval**
    - Keys only consist of complete keywords
    - Routs to a single destination
  - **Approximate retrieval**
    - Keys consist of partial keywords, wildcards
    - Routs to multiple destinations
Supporting the Rudder Agent Framework

- Agents communication
  - associatively reading, writing, and extracting tuples
- Agent coordination protocols
  - Decentralized election protocol
    - Based on wait-free consensus protocols
      - Resilient to node/link failures
  - Discovery protocol
    - Registry implemented using XML tuples
    - Element registered using Out
    - Element unregistered using In
    - Elements discovered using Rd/RdAll operation
  - Interaction protocol
    - Contract-Net protocol
    - Two agent bargaining protocol
- Workflow engine

Implementation/Deployment Overview

- Current implementation builds on JXTA
  - SquidTON, Squid, Comet and Meteor layers are implemented as event-driven JXTA services

- Deployments include
  - Campus Grid @ Rutgers
  - Orbit wireless testbed (400 nodes)
  - PlanetLab wide-area testbed
    - At least one node selected from each continent
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The Instrumented Oil Field of the Future (UT-CSM, UT-IG, RU, OSU, UMD, ANL)

• Production of oil and gas can take advantage of installed sensors that will monitor the reservoir's state as fluids are extracted
• Knowledge of the reservoir's state during production can result in better engineering decisions
  – economical evaluation; physical characteristics (bypassed oil, high pressure zones); productions techniques for safe operating conditions in complex and difficult areas

Detect and track changes in data during production
Invert data for reservoir properties
Detect and track reservoir changes
Assimilate data & reservoir properties into the evolving reservoir model
Use simulation and optimization to guide future production, future data acquisition strategy

Effective Oil Reservoir Management: Well Placement/Configuration

- Why is it important
  - Better utilization/cost-effectiveness of existing reservoirs
  - Minimizing adverse effects to the environment
Effective Oil Reservoir Management: Well Placement/Configuration

• What needs to be done
  – *Exploration of possible well placements and configurations for optimized production strategies*
  – *Understanding field properties and interactions between and across subdomains*
  – *Tracking and understanding long term changes in field characteristics*

• Challenges
  – *Geologic uncertainty: Key engineering properties unattainable*
  – *Large search space: Infinitely many production strategies possible*
  – *Complex physical properties and interactions.*
  – *Complex numerical models*
An Autonomic Well Placement/Configuration Workflow

If guess not in DB:

- Instantiate IPARS with guess as parameter.

If guess in DB:

- Send response to Clients and get new guess from Optimizer.

**Generate Guesses**
- SPSA
- VFSA
- Exhaustive Search

**Send Guesses**

- Optimization Service
- IPARS Factory
- MySQL Database
- DISCOVER

- DISCOVER notifies Clients to interact with IPARS.

**Start Parallel IPARS Instances**

**Instance connects to DISCOVER**

**Send guesses**

- DISCOVER

**AutoMate Programming System/Grid Middleware**

**History/Archived Data**

- Sensor/Context Data

- Oil prices, weather, etc.
"Autonomic Oil Well Placement/Configuration"

Permeability

Pressure contours
3 wells, 2D profile

Contours of $NEval(y,z,500)(10)$

Requires $NYxNZ (450)$ evaluations. Minimum appears here.

VFSA solution: “walk”: found after 20 (81) evaluations

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Conclusion

- Pervasive Grid Environments & Next Generation Scientific Investigation
  - Knowledge-based, data and information driven, context-aware, computationally intensive
  - Unprecedented opportunity for global scientific investigation
    - can enable accurate solutions to complex applications; provide dramatic insights into complex phenomena
  - Unprecedented research challenges
    - scale, complexity, heterogeneity, dynamism, reliability, uncertainty, …
    - applications, algorithms, measurements, data/information, software
  - Project AutoMate: Autonomic Computational Science on the Grid
    - semantic + autonomies
    - Accord, Rudder/Comet, Meteor, Squid, Topos, …

- More Information, publications, software
  - www.caip.rutgers.edu/~parashar/
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• Key CE/CS Collaborators
  – Rutgers Univ.
    • D. Silver, D. Raychaudhuri, P. Meer, M. Bushnell, etc.
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  – Idaho National Laboratory
    • R. Versteeg
  – PPPL
    • R. Samtaney
  – ASCI/CACR, Caltech
    • J. Cummings
Thank you!