Introduction to The Globus Toolkit™

The Globus Project™

Argonne National Laboratory

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http://www.globus.org/

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Globus Toolkit™

- A software toolkit addressing key technical problems in the development of Grid enabled tools, services, and applications
  - Offer a modular “bag of technologies”
  - Enable *incremental* development of grid-enabled tools and applications
  - Implement standard Grid protocols and APIs
  - Make available under liberal open source license

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General Approach

- Define Grid protocols & APIs
  - Protocol-mediated access to remote resources
  - Integrate and extend existing standards
  - “On the Grid” = speak “Intergrid” protocols
- Develop a reference implementation
  - Open source Globus Toolkit
  - Client and server SDKs, services, tools, etc.
- Grid-enable wide variety of tools
  - Globus Toolkit, FTP, SSH, Condor, SRB, MPI, ...
- Learn through deployment and applications

Key Protocols

- The Globus Toolkit™ centers around four key protocols
  - Connectivity layer:
    - *Security*: Grid Security Infrastructure (GSI)
  - Resource layer:
    - *Resource Management*: Grid Resource Allocation Management (GRAM)
    - *Information Services*: Grid Resource Information Protocol (GRIP)
    - *Data Transfer*: Grid File Transfer Protocol (GridFTP)
- Also key collective layer protocols
  - Info Services, Replica Management, etc.

The Globus Toolkit™:
APIs

Role of APIs

- While we focus heavily on protocols, the Globus Toolkit is an implementation, and as such requires APIs
  - Globus Toolkit implemented in C
  - Great effort has gone into implementing robust, consistent, and flexible APIs
- APIs in other languages also available
  - E.g. Java & Python CoG Kits

Three Types of API/SDK

1) Portability and convenience API/SDKs
2) API/SDKs implementing the four key Connectivity and Resource layer protocols
3) Collective layer API/SDKs

- This tutorial focuses primarily on the functionality available in #2 and #3
- Developer tutorial includes in-depth API discussions of all three

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Portability and Convenience API

- globus_common
  - Module activation/deactivation
  - Threads, mutual exclusion, conditions
  - Callback/event driver
  - Libc wrappers
  - Convenience modules (list, hash, etc).

Connectivity APIs

- globus_io
  - TCP, UDP, IP multicast, and file I/O
  - Integrates GSI security
  - Asynchronous and synchronous interfaces
  - Attribute based control of behavior
- Nexus (Deprecated)
  - Higher level, active message style comms
  - Built on globus_io, but without security
- MPICH-G2
  - High level, MPI (send/receive) interface
  - Built on globus_io and native MPI

The Globus Toolkit™:
Security

Security Terminology

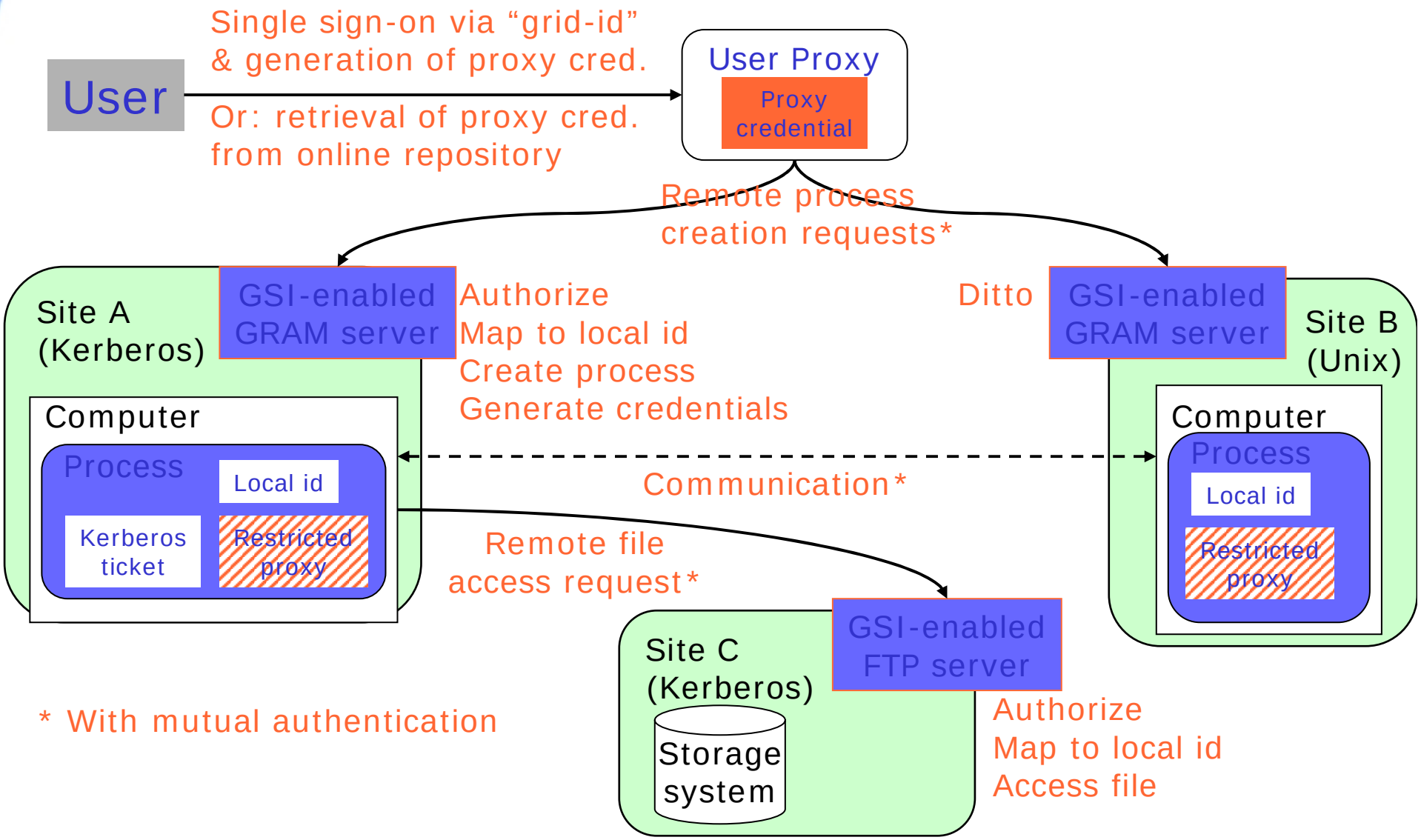
- Authentication: Establishing identity
- Authorization: Establishing rights
- Message protection
  - Message integrity
  - Message confidentiality
- Non-repudiation
- Digital signature
- Accounting
- Certificate Authority (CA)

Why Grid Security is Hard

- Resources being used may be valuable & the problems being solved sensitive
- Resources are often located in distinct administrative domains
  - Each resource has own policies & procedures
- Set of resources used by a single computation may be large, dynamic, and unpredictable
  - Not just client/server, requires delegation
- It must be broadly available & applicable
  - Standard, well-tested, well-understood protocols; integrated with wide variety of tools

GSI in Action

"Create Processes at A and B that Communicate & Access Files at C"



Grid Security Requirements

User View

1) Easy to use
2) Single sign-on
3) Run applications
   ftp,ssh,MPI,Condor,Web,...
4) User based trust model
5) Proxies/agents (delegation)

Resource Owner View

1) Specify local access control
2) Auditing, accounting, etc.
3) Integration w/ local system
   Kerberos, AFS, license mgr.
4) Protection from compromised resources

Developer View

API/SDK with authentication, flexible message protection, flexible communication, delegation, ...

Direct calls to various security functions (e.g. GSS-API)

Or security integrated into higher-level SDKs:

E.g. GlobusIO, Condor-G, MPICH-G2, HDF5, etc.

Candidate Standards

- Kerberos 5
  - Fails to meet requirements:
    - > Integration with various local security solutions
    - > User based trust model
- Transport Layer Security (TLS/SSL)
  - Fails to meet requirements:
    - > Single sign-on
    - > Delegation

Grid Security Infrastructure (GSI)

- Extensions to standard protocols & APIs
  - Standards: SSL/TLS, X.509 & CA, GSS-API
  - Extensions for single sign-on and delegation
- Globus Toolkit reference implementation of GSI
  - SSLeay/OpenSSL + GSS-API + SSO/delegation
  - Tools and services to interface to local security
    - > Simple ACLs; SSLK5/PKINIT for access to K5, AFS; ...
  - Tools for credential management
    - > Login, logout, etc.
    - > Smartcards
    - > MyProxy: Web portal login and delegation
    - > K5cert: Automatic X.509 certificate creation

Review of Public Key Cryptography

- Asymmetric keys
  - A **private** key is used to encrypt data.
  - A **public** key can decrypt data encrypted with the private key.
- An X.509 certificate includes…
  - Someone's subject name (user ID)
  - Their public key
  - A "signature" from a Certificate Authority (CA) that:
    - > Proves that the certificate came from the CA.
    - > Vouches for the subject name
    - > Vouches for the binding of the public key to the subject

Public Key Based Authentication

- User sends certificate over the wire.
- Other end sends user a challenge string.
- User encodes the challenge string with private key
  - Possession of private key means you can authenticate as subject in certificate
- Public key is used to decode the challenge.
  - If you can decode it, you know the subject
- Treat your private key carefully!!
  - Private key is stored only in well-guarded places, and only in encrypted form

X.509 Proxy Certificate

- Defines how a short term, restricted credential can be created from a normal, long-term X.509 credential
  - A “proxy certificate” is a special type of X.509 certificate that is signed by the normal end entity cert, or by another proxy
  - Supports single sign-on & delegation through “impersonation”
  - Currently an IETF draft

User Proxies

- Minimize exposure of user's private key
- A temporary, X.509 proxy credential for use by our computations
  - We call this a user proxy certificate
  - Allows process to act on behalf of user
  - User-signed user proxy cert stored in local file
  - Created via "grid-proxy-init" command
- Proxy's private key is not encrypted
  - Rely on file system security, proxy certificate file must be readable only by the owner

Delegation

- Remote creation of a user proxy
- Results in a new private key and X.509 proxy certificate, signed by the original key
- Allows remote process to act on behalf of the user
- Avoids sending passwords or private keys across the network

Globus Security APIs

- Generic Security Service (GSS) API
  - IETF standard
  - Provides functions for authentication, delegation, message protection
  - Decoupled from any particular communication method
- GSS-API Extensions (GGF draft)
  - Small extensions to GSS
- But GSS-API is complicated, so we also provide the easier globus_gss_assist API.
- GSI-enabled SASL is also provided

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Results

- GSI adopted by 100s of sites, 1000s of users
  - Globus CA has issued >4000 certs (user & host), >1500 currently active; other CAs active
- Rollouts are currently underway all over:
  - NSF Teragrid, NASA Information Power Grid, DOE Science Grid, European Data Grid, etc.
- Integrated in research & commercial apps
  - GrADS testbed, Earth Systems Grid, European Data Grid, GriPhyN, NEESgrid, etc.
- Standardization begun in Global Grid Forum, IETF

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GSI Applications

- Globus Toolkit™ uses GSI for authentication
- Many Grid tools, directly or indirectly, e.g.
  - Condor-G, SRB, MPICH-G2, Cactus, GDMP, ...
- Commercial and open source tools, e.g.
  - ssh, ftp, cvs, OpenLDAP, OpenAFS
  - SecureCRT (Win32 ssh client)
- And since we use standard X.509 certificates, they can also be used for
  - Web access, LDAP server access, etc.

Ongoing and Future GSI Work

- Protection against compromised resources
  - Restricted delegation, smartcards
- Standardization
- Scalability in numbers of users & resources
  - Credential management
  - Online credential repositories (“MyProxy”)
  - Account management
- Authorization
  - Policy languages
  - Community authorization

Restricted Proxies

- Q: How to restrict rights of delegated proxy to a subset of those associated with the issuer?
- A: Embed restriction policy in proxy cert
  - Policy is evaluated by resource upon proxy use
  - Reduces rights available to the proxy to a subset of those held by the user
- But how to avoid policy language wars?
  - Proxy cert just contains a container for a policy specification, without defining the language
    - Container = OID + blob
  - Can evolve policy languages over time

Delegation Tracing

- Often want to know through what entities a proxy certificate has been delegated
  - Audit (retrace footsteps)
  - Authorization (deny from bad entities)
- Solved by adding information to the signed proxy certificate about each entity to which a proxy is delegated.
  - Does NOT guarantee proper use of proxy
  - Just tells you which entities were purposely involved in a delegation

Proxy Certificate Standards Work

- "Internet Public Key Infrastructure X.509 Proxy Certificate Profile"
  - draft-ietf-pkix-proxy-01.txt
    - > Draft being considered by IETF PKIX working group, and by GGF GSI working group
  - Defines proxy certificate format, including restricted rights and delegation tracing
- Demonstrated a prototype of restricted proxies at HPDC (August 2001) as part of CAS demo

Delegation Protocol Work

- "TLS Delegation Protocol"
  - draft-ietf-tls-delegation-01.txt
    - > Draft being considered by IETF TLS working group, and by GGF GSI working group
  - Defines how to remotely delegate an X.509 Proxy Certificate using extensions to the TLS (SSL) protocol
- But, may change approach here
  - Instead of embedding into TLS, carry on top of TLS
  - This is the current approach in Globus Toolkit

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GSS-API Extensions Work

- 4 years of GSS-API experience, while on the whole quite positive, has shed light on various deficiencies of GSS-API
- "GSS-API Extensions"
  - draft-ggf-gss-extensions-04.txt
    - > Draft being considered by GGF GSI working group. Not yet submitted to IETF.
  - Defines extensions to the GSS-API to better support Grid security

GSS-API Extensions

- Credential export/import
  - Allows delegated credentials to be externalized
  - Used for checkpointing a service
- Delegation at any time, in either direction
  - More rich options on use of delegation
- Restricted delegation handling
  - Add proxy restrictions to delegated cred
  - Inspect auth cert for restrictions
- Allow better mapping of GSS to TLS
  - Support TLS framing of messages

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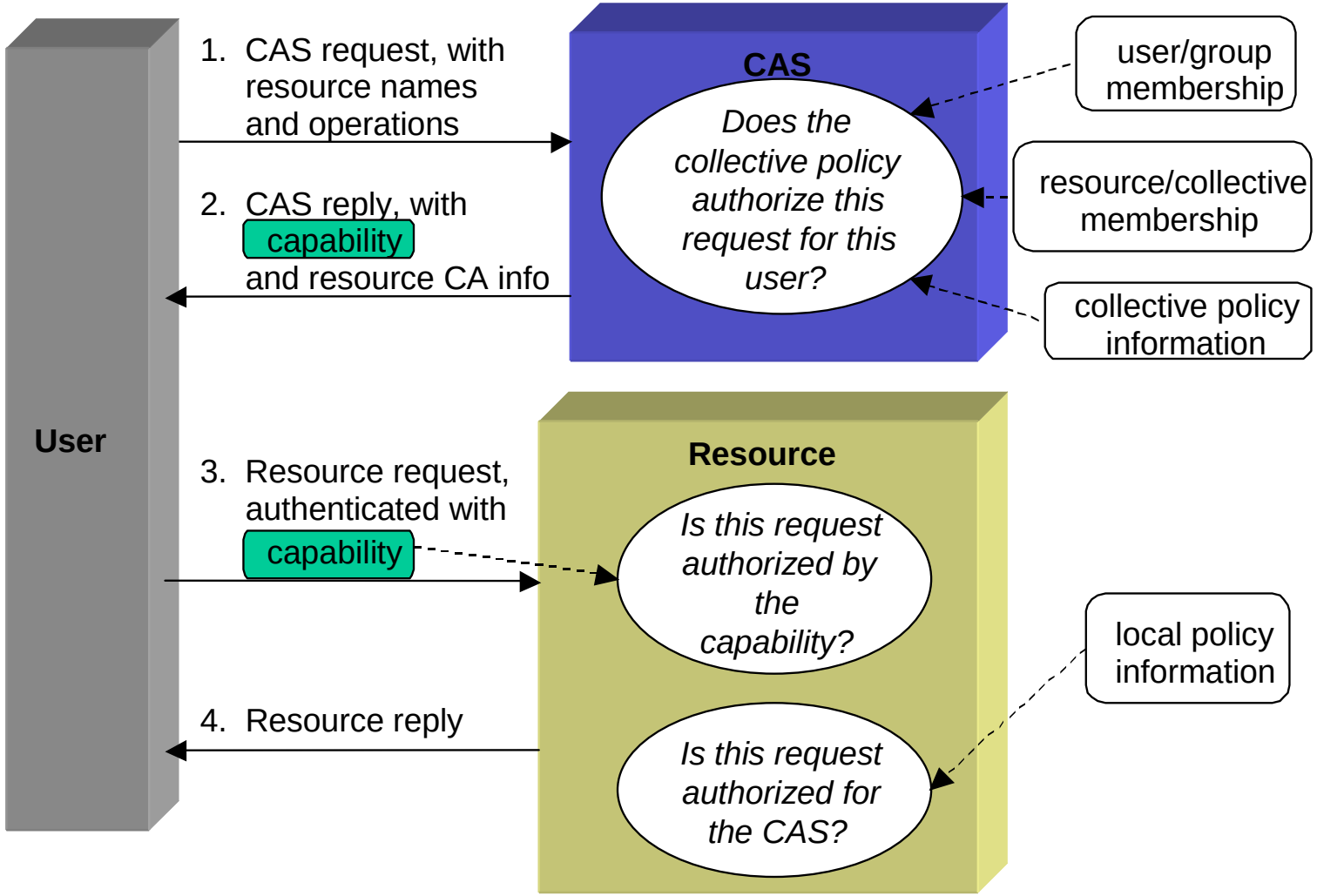
Community Authorization Service

- Question: How does a large community grant its users access to a large set of resources?
  - Should minimize burden on both the users and resource providers
- Community Authorization Service (CAS)
  - Community negotiates access to resources
  - Resource outsources fine-grain authorization to CAS
  - Resource only knows about “CAS user” credential
    - > CAS handles user registration, group membership…
  - User who wants access to resource asks CAS for a capability credential
    - > Restricted proxy of the “CAS user” cred., checked by resource

Community Authorization (Prototype shown August 2001)



Community Authorization Service

- CAS provides user community with information needed to authenticate resources
  - Sent with capability credential, used on connection with resource
  - Resource identity (DN), CA
- This allows new resources/users (and their CAs) to be made available to a community through the CAS without action on the other user's/resource's part

Authorization API

- Service providers need to perform authorization policy evaluation on:
  - Local policies
  - Policies contained in restricted proxies
- We are working on 2 API layers:
  - Low level GAA-API implementation for evaluation of policies
  - High level, very simple authorization API that can easily be embedded into services
- Still in early prototyping stage

Passport Online CA & MyProxy

- Requiring users to manage their own certs and keys is annoying and error prone
- A solution: Leverage Passport global authentication to obtain a proxy credential
  - Passport provides
    - > Globally unique user name (email address)
    - > Method of verifying ownership of the name (authentication)
    - > Re-issuance (e.g. forgotten password)
  - Passport credentials can be presented to an online CA or credential repository
    - > Creates and issues new (restricted) proxy certificate to the user on demand

Other Future Security Work

- Ease-of-use
  - Improved error message, online CA, etc.
- Improved online credential repositories
  - See MyProxy paper at HPDC
- Support for multiple user credentials
- Multi-factor authentication
- Subordinate certificate authorities for domains
  - Ease issuance of host certs for domains
- Independent Data Unit Support

Security Summary

- GSI successfully addresses wide variety of Grid security issues
- Broad acceptance, deployment, integration with tools
- Standardization on-going in IETF & GGF
- Ongoing R&D to address next set of issues
- For more information:
  - www.globus.org/research/papers.html
    - "A Security Architecture for Computational Grids"
    - "Design and Deployment of a National-Scale Authentication Infrastructure"
  - www.gridforum.org/security

The Globus Toolkit™:
Resource Management

The Challenge

- Enabling secure, controlled remote access to heterogeneous computational resources and management of remote computation
  - Authentication and authorization
  - Resource discovery & characterization
  - Reservation and allocation
  - Computation monitoring and control
- Addressed by new protocols & services
  - GRAM protocol as a basic building block
  - Resource brokering & co-allocation services
  - GSI for security, MDS for discovery

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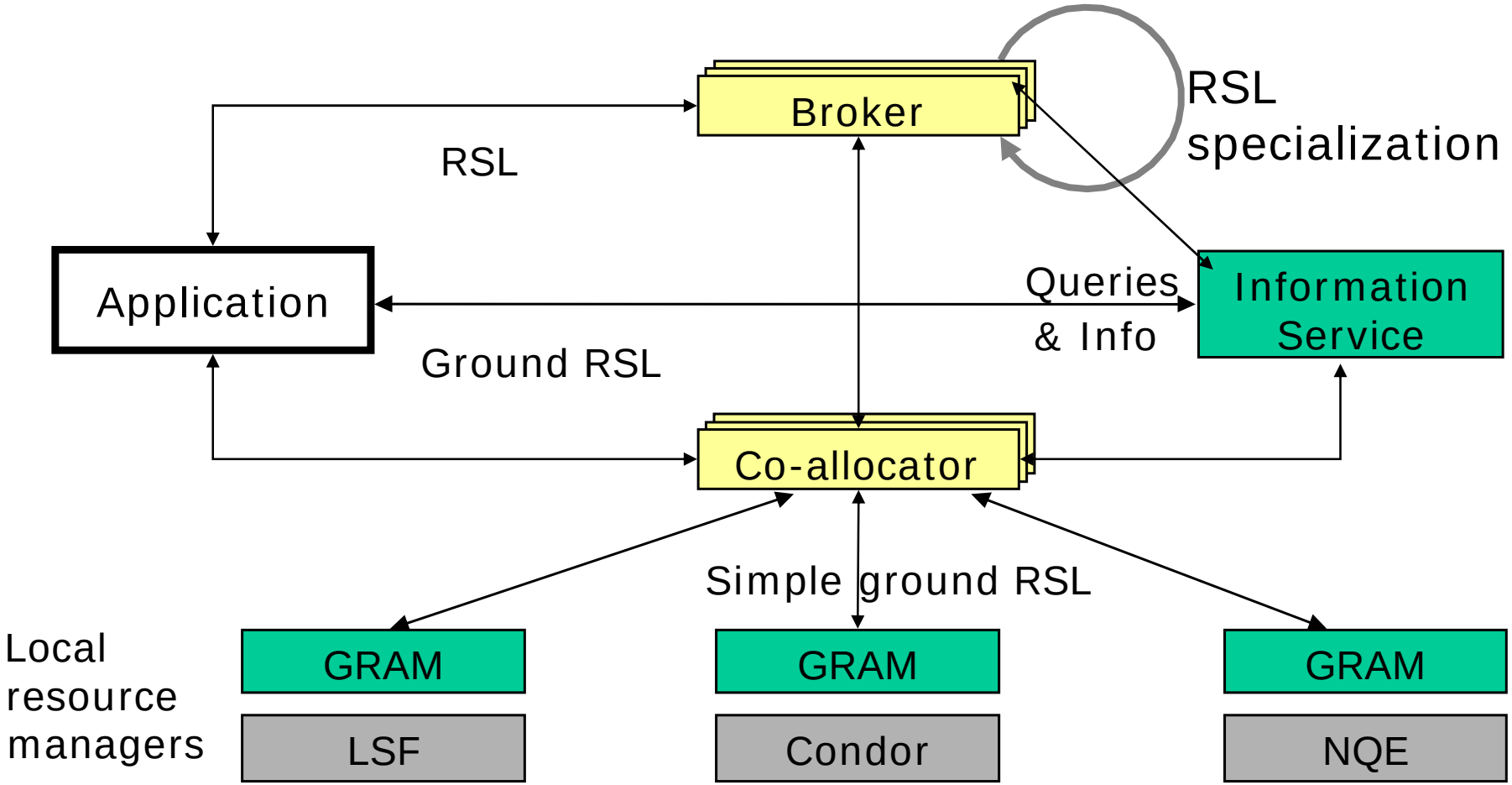
Resource Management

- The Grid Resource Allocation Management (GRAM) protocol and client API allows programs to be started on remote resources, despite local heterogeneity
- Resource Specification Language (RSL) is used to communicate requirements
- A layered architecture allows application-specific resource brokers and co-allocators to be defined in terms of GRAM services
  - Integrated with Condor, PBS, MPICH-G2, …

Resource Management Architecture



Resource Specification Language

- Common notation for exchange of information between components
  - Syntax similar to MDS/LDAP filters
- RSL provides two types of information:
  - Resource requirements: Machine type, number of nodes, memory, etc.
  - Job configuration: Directory, executable, args, environment
- Globus Toolkit provides an API/SDK for manipulating RSL

RSL Syntax

- Elementary form: parenthesis clauses
  - (attribute op value [value ...])
- Operators Supported:
  - <, <=, =, >=, > , !=
- Some supported attributes:
  - executable, arguments, environment, stdin, stdout, stderr, resourceManagerContact, resourceManagerName
- Unknown attributes are passed through
  - May be handled by subsequent tools

Constraints: “&”

- For example:

  & (count>=5) (count<=10)
  (max_time=240) (memory>=64)
  (executable=myprog)

- “Create 5-10 instances of myprog, each on a machine with at least 64 MB memory that is available to me for 4 hours”

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Disjunction: "|"

- For example:

```
& (executable=myprog)
   ( | (&(count=5)(memory>=64))
        (&(count=10)(memory>=32)))
```

- Create 5 instances of myprog on a machine that has at least 64MB of memory, or 10 instances on a machine with at least 32MB of memory

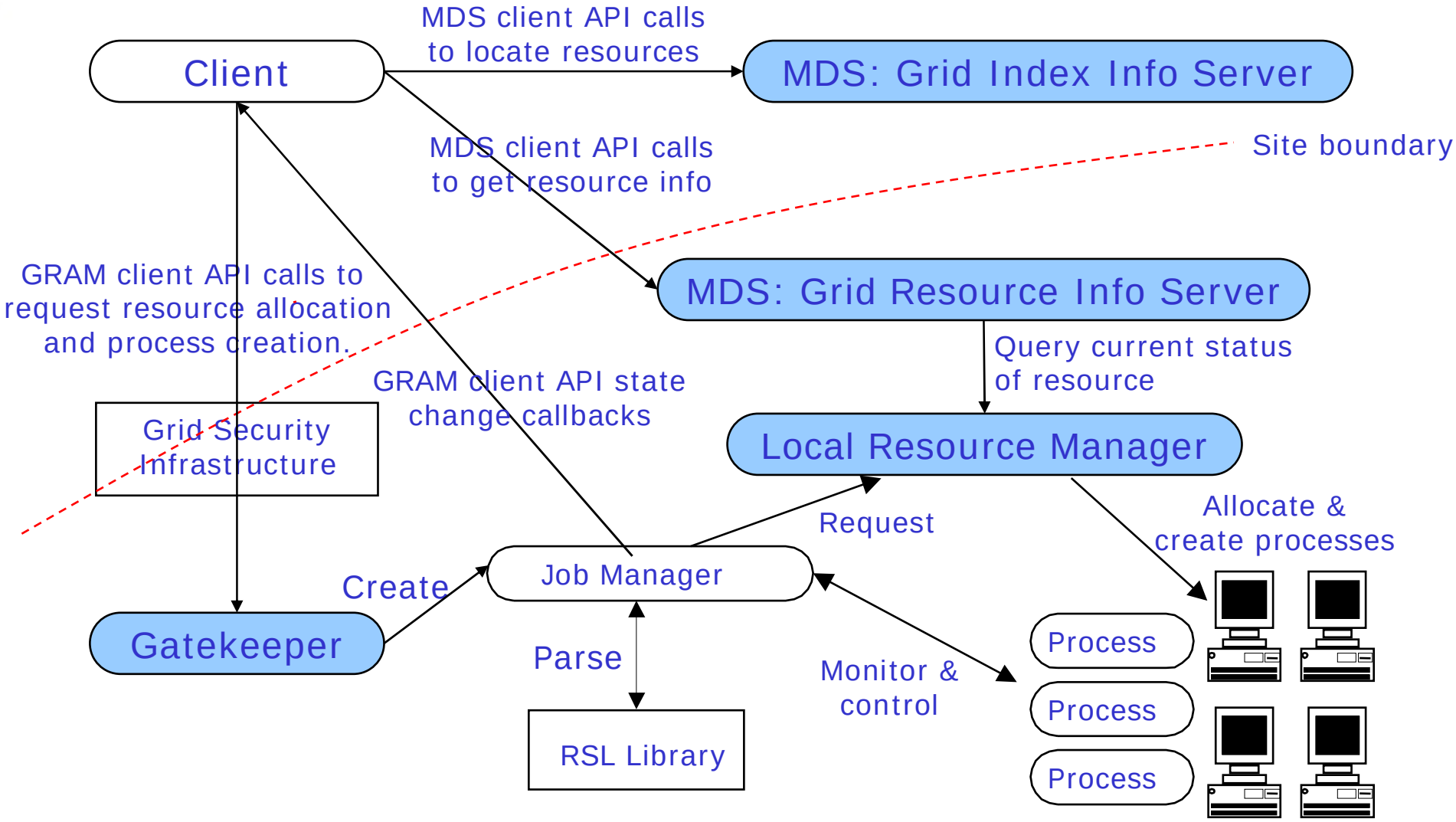
GRAM Protocol

- GRAM-1: Simple HTTP-based RPC
  - Job request
    - > Returns a “job contact”: Opaque string that can be passed between clients, for access to job
  - Job cancel, status, signal
  - Event notification (callbacks) for state changes
    - > Pending, active, done, failed, suspended
- GRAM-1.5 (U Wisconsin contribution)
  - Add reliability improvements
    - > Once-and-only-once submission
    - > Recoverable job manager service
    - > Reliable termination detection
- GRAM-1.6: Incremental additions
- GRAM-2: Future overhaul, based on Web services

Globus Toolkit Implementation

- Gatekeeper
  - Single point of entry
  - Authenticates user, maps to local security environment, runs service
  - In essence, a “secure inetd”
- Job manager
  - A gatekeeper service
  - Layers on top of local resource management system (e.g., PBS, LSF, etc.)
  - Handles remote interaction with the job

GRAM Components



Co-allocation

- Simultaneous allocation of a resource set
  - Handled via optimistic co-allocation based on free nodes or queue prediction
  - In the future, advance reservations will also be supported (already in prototype)
- Globus APIs/SDKs support the co-allocation of specific multi-requests
  - Uses a Globus component called the Dynamically Updated Request Online Co-allocator (DUROC)

Multirequest: “+”

- A multirequest allows us to specify multiple resource needs, for example

```
+ (& (count=5)(memory>=64)
       (executable=p1))
   (&(network=atm) (executable=p2))
```

  - Execute 5 instances of p1 on a machine with at least 64M of memory
  - Execute p2 on a machine with an ATM connection
- Multirequests are central to co-allocation

A Co-allocation Multirequest

```
+( & (resourceManagerContact=
     "flash.isi.edu:754:/C=US/.../CN=flash.isi.edu-fork")
       (count=1)
       (label="subjob A")
       (executable=my_app1)
   )
   ( & (resourceManagerContact=
        "sp139.sdsc.edu:8711:/C=US/.../CN=sp097.sdsc.edu-lsf")
       (count=2)
       (label="subjob B")
       (executable=my_app2)
   )
```

Different counts

Different resource managers

Different executables

Job Submission Interfaces

- Globus Toolkit includes several command line programs for job submission
  - globus-job-run: Interactive jobs
  - globus-job-submit: Batch/offline jobs
  - globusrun: Flexible scripting infrastructure
- Others are building better interfaces
  - General purpose
    - > Condor-G, PBS, GRD, Hotpage, etc
  - Application specific
    - > ECCE', Cactus, Web portals

globus-job-run

- For running of interactive jobs
- Additional functionality beyond rsh
  - Ex: Run 2 process job w/ executable staging

    ```
    globus-job-run -: host –np 2 –s myprog arg1 arg2
    ```
  - Ex: Run 5 processes across 2 hosts

    ```
    globus-job-run \
            -: host1 –np 2 –s myprog.linux arg1 \
            -: host2 –np 3 –s myprog.aix arg2
    ```
  - For list of arguments run:

    ```
    globus-job-run -help
    ```

globus-job-submit

- For running of batch/offline jobs
  - globus-job-submit — Submit job
    - > Same interface as globus-job-run
    - > Returns immediately
  - globus-job-status — Check job status
  - globus-job-cancel — Cancel job
  - globus-job-get-output — Get job stdout/err
  - globus-job-clean — Cleanup after job

globusrun

- Flexible job submission for scripting
  - Uses an RSL string to specify job request
  - Contains an embedded globus-gass-server
    - > Defines GASS URL prefix in RSL substitution variable: (stdout=$(GLOBUSRUN_GASS_URL)/stdout)
  - Supports both interactive and offline jobs
- Complex to use
  - Must write RSL by hand
  - Must understand its esoteric features
  - Generally you should use globus-job-* commands instead

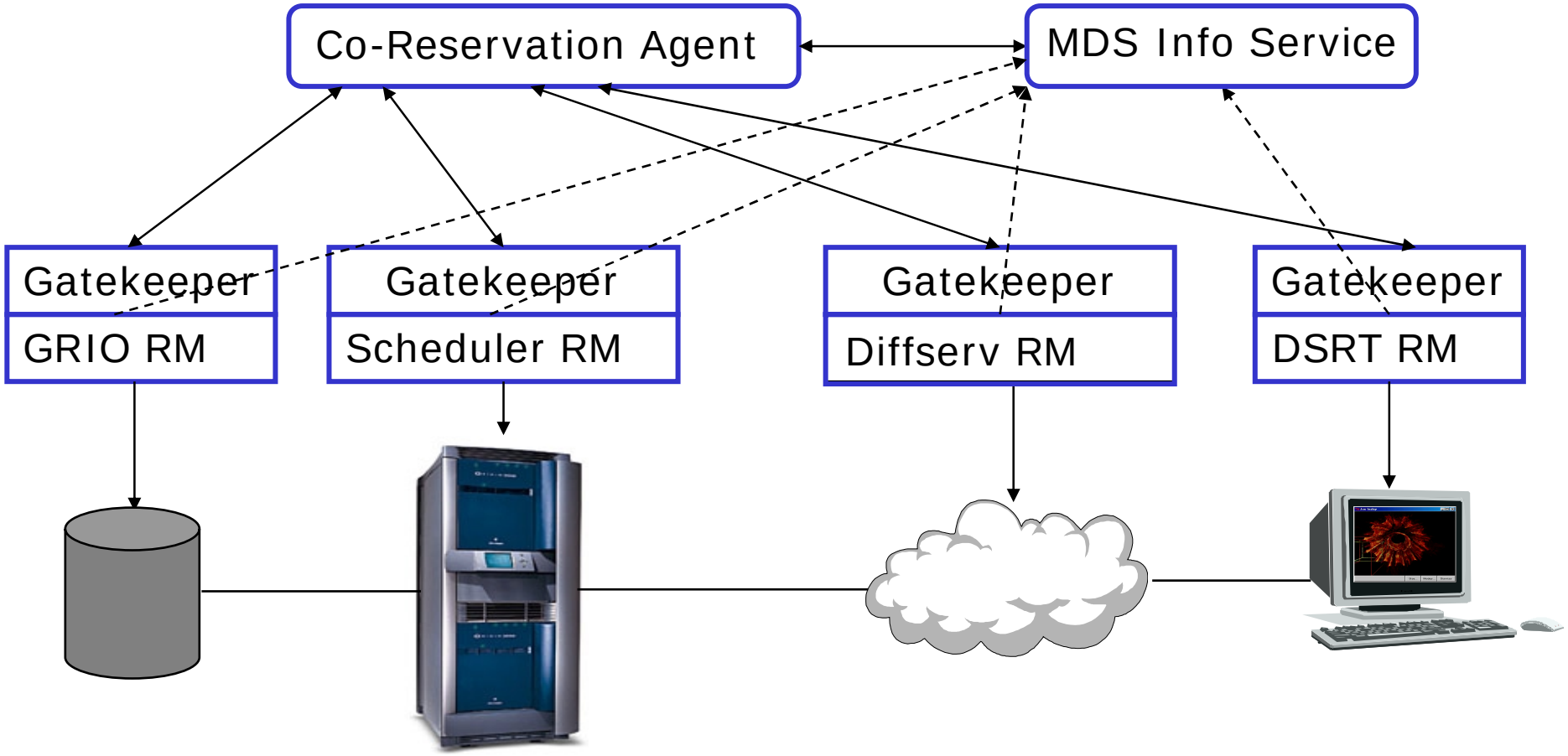
Resource Management APIs

- The globus_gram_client API provides access to all of the core job submission and management capabilities, including callback capabilities for monitoring job status.
- The globus_rsl API provides convenience functions for manipulating and constructing RSL strings.
- The globus_gram_myjob allows multi-process jobs to self-organize and to communicate with each other.
- The globus_duroc_control and globus_duroc_runtime APIs provide access to multirequest (co-allocation) capabilities.

Advance Reservation and Other Generalizations

- General-purpose Architecture for Reservation and Allocation (GARA)
  - 2nd generation resource management services
- Broadens GRAM on two axes
  - Generalize to support various resource types
    - CPU, storage, network, devices, etc.
  - Advance reservation of resources, in addition to allocation
- Currently a research prototype

GARA: The Big Picture



Resource Management Futures: GRAM-1.6 (planned for 2Q02)

- Asynchronous client API
- New RSL attribute to pass through scheduler specific commands
  - No more piggy-backing on the environment attributes
- File staging
  - scratch dir, input, output
- Advanced output management
  - Stream/store stdout and stderr to multiple destinations

Resource Management Futures: GRAM-2 (planned for late 2002)

- Advance reservations
  - As prototyped in GARA in previous 2 years
- Multiple resource types
  - Manage anything: storage, networks, etc., etc.
- Recoverable requests, timeout, etc.
- Better lifetime management
- Policy evaluation points for restricted proxies
- Use of Web Services (WSDL, SOAP)

Karl Czajkowski, Steve Tuecke, others

The Globus Toolkit™:
Data Management

Data Grid Problem

- "Enable a geographically distributed community [of thousands] to pool their resources in order to perform sophisticated, computationally intensive analyses on Petabytes of data"
- Note that this problem:
  - Is common to many areas of science
  - Overlaps strongly with other Grid problems

Major Data Grid Projects

- Earth System Grid (DOE Office of Science)
  - DG technologies, climate applications
- European Data Grid (EU)
  - DG technologies & deployment in EU
- GriPhyN (NSF ITR)
  - Investigation of “Virtual Data” concept
- Particle Physics Data Grid (DOE Science)
  - DG applications for HENP experiments

Data Grids for High Energy Physics

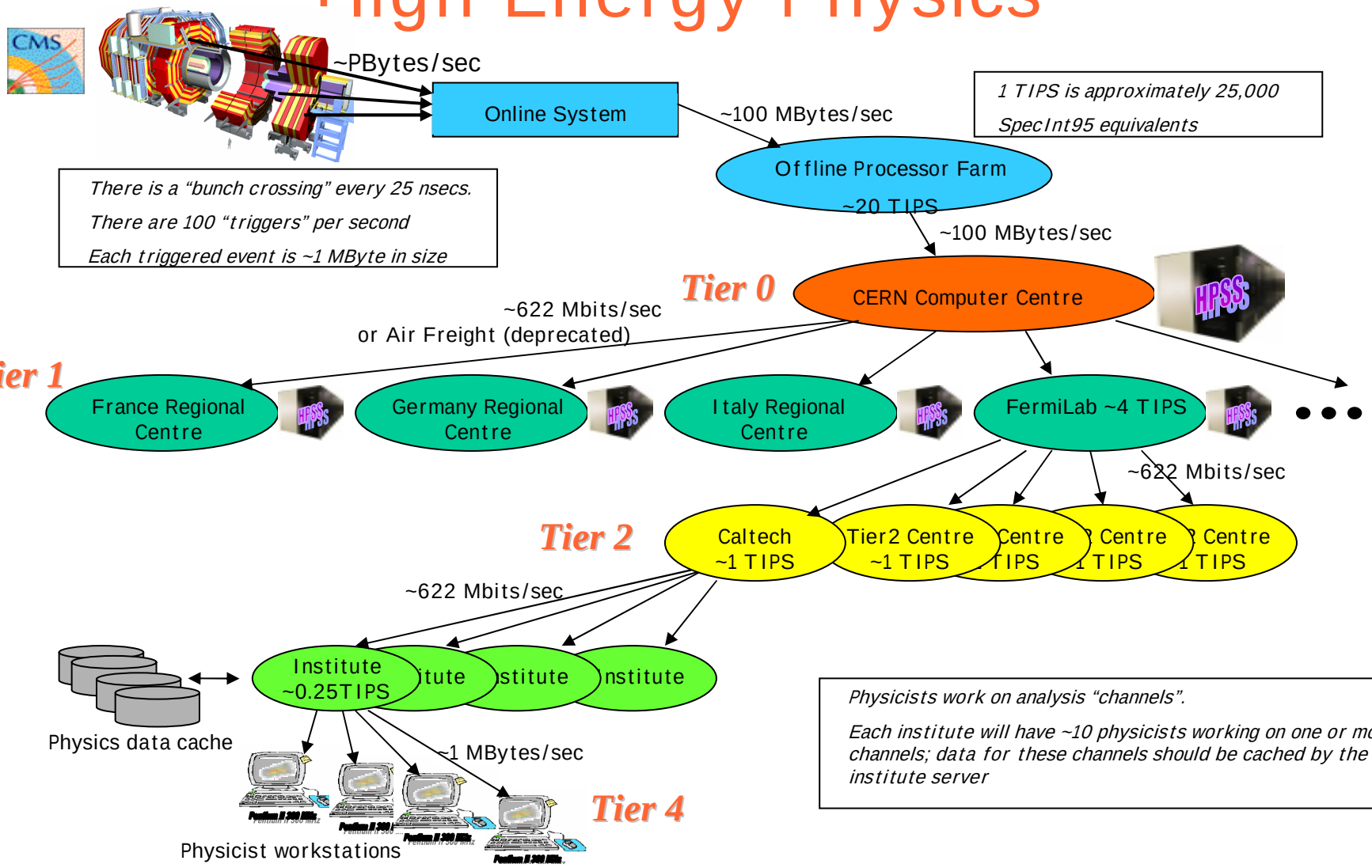


Image courtesy Harvey Newman, Caltech

Data Intensive Issues Include …

- Harness [potentially large numbers of] data, storage, network resources located in distinct administrative domains
- Respect local and global policies governing what can be used for what
- Schedule resources efficiently, again subject to local and global constraints
- Achieve high performance, with respect to both speed and reliability
- Catalog software and virtual data

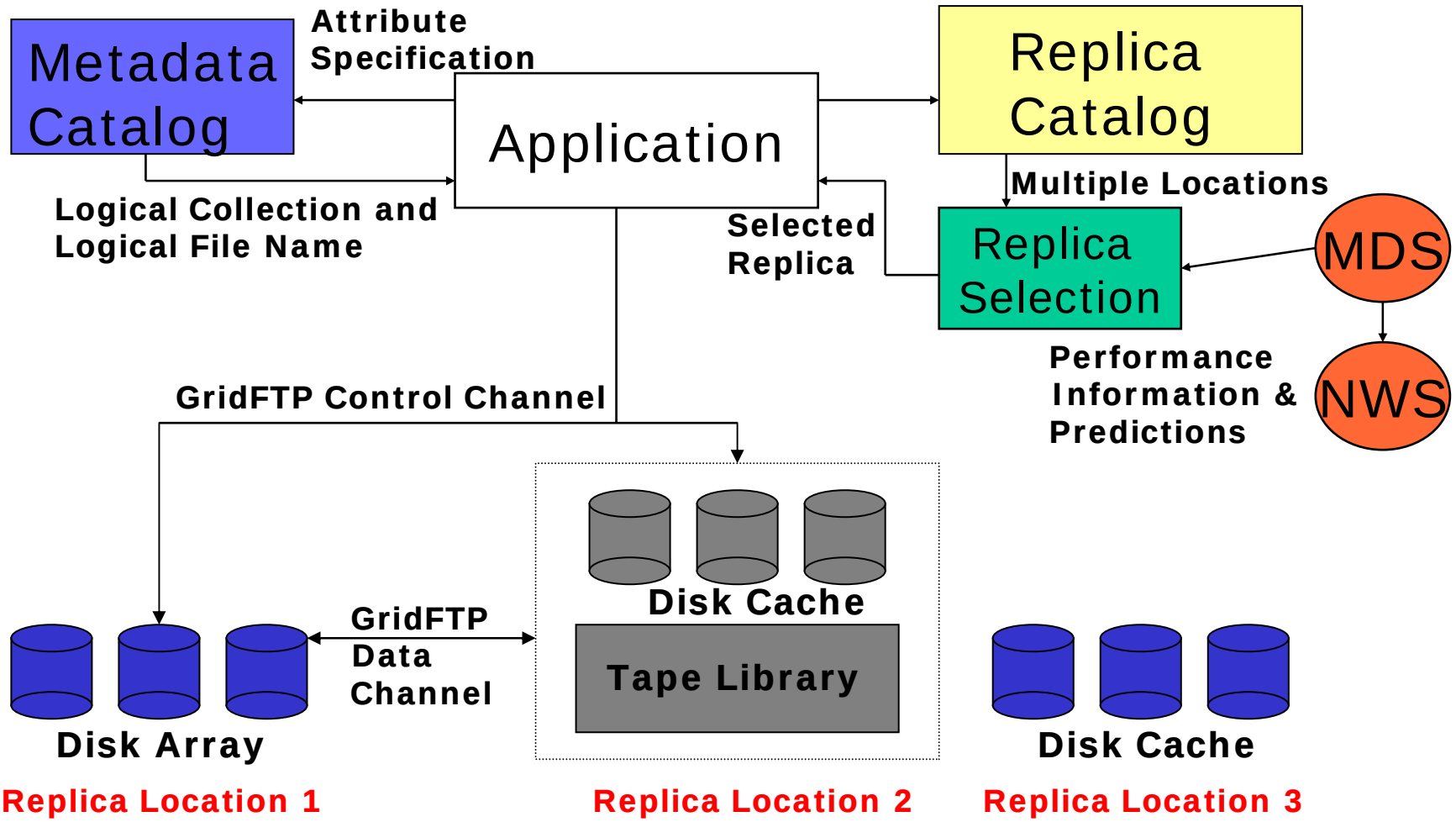
Data Intensive Computing and Grids

- The term “Data Grid” is often used
  - Unfortunate as it implies a distinct infrastructure, which it isn’t; but easy to say
- Data-intensive computing shares numerous requirements with collaboration, instrumentation, computation, …
  - Security, resource mgt, info services, etc.
- Important to exploit commonalities as very unlikely that multiple infrastructures can be maintained
- Fortunately this seems easy to do!

Examples of Desired Data Grid Functionality

- High-speed, reliable access to remote data
- Automated discovery of “best” copy of data
- Manage replication to improve performance
- Co-schedule compute, storage, network
- “Transparency” wrt delivered performance
- Enforce access control on data
- Allow representation of “global” resource allocation policies

A Model Architecture for Data Grids



Globus Toolkit Components

Two major Data Grid components:

1. Data Transport and Access

- Common protocol
  - Secure, efficient, flexible, extensible data movement
- Family of tools supporting this protocol

2. Replica Management Architecture

- Simple scheme for managing:
  - multiple copies of files
  - collections of files

Motivation for a Common Data Access Protocol

- Existing distributed data storage systems
  - DPSS, HPSS: focus on high-performance access, utilize parallel data transfer, striping
  - DFS: focus on high-volume usage, dataset replication, local caching
  - SRB: connects heterogeneous data collections, uniform client interface, metadata queries
- Problems
  - Incompatible (and proprietary) protocols
    - > Each require custom client
    - > Partitions available data sets and storage devices
  - Each protocol has subset of desired functionality

A Common, Secure, Efficient Data Access Protocol

- Common, *extensible* transfer protocol
  - Common protocol means all can interoperate
- Decouple low-level data transfer mechanisms from the storage service
- Advantages:
  - New, specialized storage systems are automatically compatible with existing systems
  - Existing systems have richer data transfer functionality
- Interface to many storage systems
  - HPSS, DPSS, file systems
  - Plan for SRB integration

Access/Transport Protocol Requirements

- Suite of communication libraries and related tools that support
  - GSI, Kerberos security
  - Third-party transfers
  - Parameter set/negotiate
  - Partial file access
  - Reliability/restart
  - Large file support
  - Data channel reuse
  - Integrated instrumentation
  - Loggin/audit trail
  - Parallel transfers
  - Striping (cf DPSS)
  - Policy-based access control
  - Server-side computation
  - Proxies (firewall, load bal)
- All based on a standard, widely deployed protocol

And The Protocol Is ... GridFTP

- Why FTP?
  - Ubiquity enables interoperation with many commodity tools
  - Already supports many desired features, easily extended to support others
  - Well understood and supported
- We use the term GridFTP to refer to
  - Transfer protocol which meets requirements
  - Family of tools which implement the protocol
- Note GridFTP > FTP
- Note that despite name, GridFTP is not restricted to file transfer!

GridFTP: Basic Approach

- FTP protocol is defined by several IETF RFCs
- Start with most commonly used subset
  - Standard FTP: get/put etc., 3rd-party transfer
- Implement standard but often unused features
  - GSS binding, extended directory listing, simple restart
- Extend in various ways, while preserving interoperability with existing servers
  - Striped/parallel data channels, partial file, automatic & manual TCP buffer setting, progress monitoring, extended restart

GridFTP Protocol Specifications

- Existing standards
  - RFC 949: File Transfer Protocol
  - RFC 2228: FTP Security Extensions
  - RFC 2389: Feature Negotiation for the File Transfer Protocol
  - Draft: FTP Extensions
- New drafts
  - GridFTP: Protocol Extensions to FTP for the Grid
    - > Grid Forum Data Working Group

GridFTP vs. WebDAV

- WebDAV extends http for remote data access
  - Combines control and data over single channel
- FTP splits control and data
  - Supports multiple, user selectable data channel protocols
- Advantage to split channels
  - Third party transfers handled cleanly
  - Can (cleanly) define new data channel protocols
    - > E.g. parallel/striped transfer, automatic TCP buffer/window negotiation, non-TCP based protocols, etc.
  - Amenable to high-performance proxies
    - > E.g. For firewalls, load balancing, etc.

The GridFTP Family of Tools

- Patches to existing FTP code
  - GSI-enabled versions of existing FTP client and server, for high-quality production code
- Custom-developed libraries
  - Implement full GridFTP protocol, targeting custom use, high-performance
- Custom-developed tools
  - Servers and clients with specialized functionality and performance

Family of Tools: Patches to Existing Code

- Patches to standard FTP clients and servers
  - gsi-ncftp: Widely used client
  - gsi-wuftpd: Widely used server
  - GSI modified HPSS pftpd
  - GSI modified Unitree ftpd
- Provides high-quality, production ready, FTP clients and servers
- Integration with common mass storage systems
- Some do not support the full GridFTP protocol

Family of Tools: Custom Developed Libraries

- Custom developed libraries
  - globus_ftp_control: Low level FTP driver
    - > Client & server protocol and connection management
  - globus_ftp_client: Simple, reliable FTP client
    - > Plugins for restart, logging, etc.
  - globus_gass_copy: Simple URL-to-URL copy library, supporting (gsi-)ftp, http(s), file URLs
- Implement full GridFTP protocol
- Various levels of libraries, allowing implementation of custom clients and servers
- Tuned for high performance on WAN

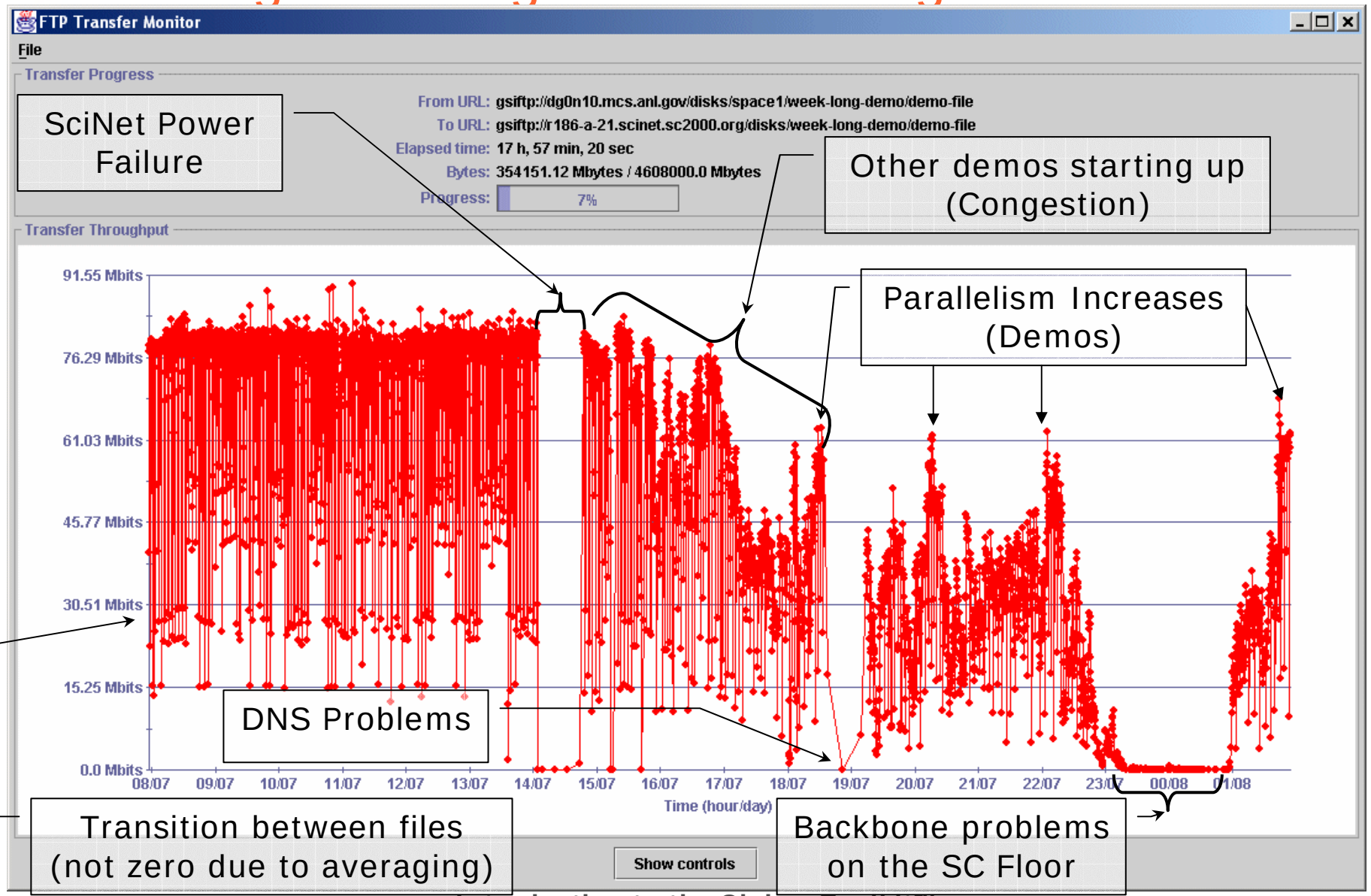
Family of Tools: Custom Developed Programs

- Simple production client
  - globus-url-copy: Simple URL-to-URL copy
- Experimental FTP servers
  - Striped FTP server (ala.DPSS): MPI-IO backend
  - Multi-threaded FTP server with parallel channels
  - Firewall FTP proxy: Securely and efficiently allow transfers through firewalls
  - Load balancing FTP proxy: Large data centers
- Experimental FTP clients
  - POSIX file interface

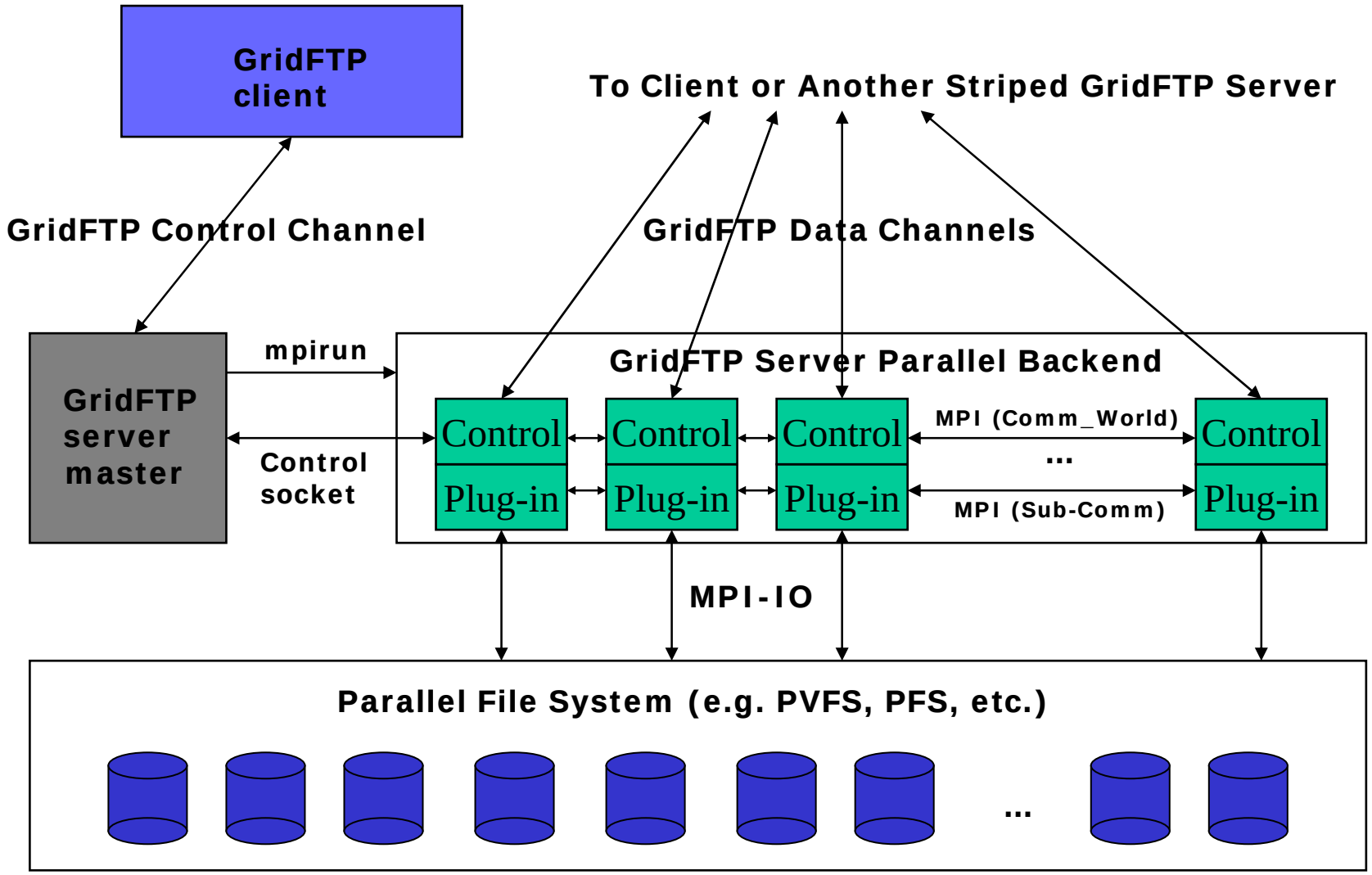
globus_ftp_client Plug-ins

- globus_ftp_client is simple API/SDK:
  - get, put, 3rd party transfer, cd, mkdir, etc.
  - All data is to/from memory buffers
    - > Optimized to avoid any data copies
  - Plug-in interface
    - > Interface to one or more plug-ins:
      - Callouts for all interesting protocol events
      - Callins to restart a transfer
    - > Can support:
      - Monitor performance
      - Monitor for failure
      - Automatic retry: Customized for various approaches

GridFTP at SC'2000: Long-Running Dallas-Chicago Transfer



(Prototype) Striped GridFTP Server



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Striped GridFTP Plug-in Interface

- Given a RETR or STOR request:
  - Control calls plug-in to determine which nodes should participate in the request
  - Control creates an MPI sub-comm for nodes
  - Control calls plug-in to perform the transfer
    - > Includes request info, communicator, globus_ftp_control_handle_t
  - Plug-in does I/O to backend
    - > MPI-IO, PVFS, Unix I/O, Raw I/O, etc.
  - Plug-in uses globus_ftp_control_data_*() functions to send/receive data on GridFTP data channels

Striped GridFTP Performance

- At SC'00, used first prototype:
  - Transfer between Dallas and LBNL
  - 8 node Linux clusters on each end
  - OC-48, 2.5Gb/s link (NTON)
  - Peaks over 1.5Gb/s
    - > Limited by disk bandwidth on end-points
  - 5 second peaks over 1Gb/s
  - Sustained 530Mb/s for 1 hr (238GB transfer)
    - > Had not yet implemented large files or data channel reuse.
    - > 2GB file took <20 seconds. New data channel sockets connected for each transfer.
    - > Explains difference between sustained and peak.

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A Word on GASS

- The Globus Toolkit provides services for file and executable staging and I/O redirection that work well with GRAM. This is known as Globus Access to Secondary Storage (GASS).
- GASS uses GSI-enabled HTTP as the protocol for data transfer, and a caching algorithm for copying data when necessary.
- The globus_gass, globus_gass_transfer, and globus_gass_cache APIs provide programmer access to these capabilities, which are already integrated with the GRAM job submission tools.

Replica Management

- Maintain a mapping between logical names for files and collections and one or more physical locations
- Important for many applications
  - Example: CERN HLT data
    - > Multiple petabytes of data per year
    - > Copy of everything at CERN (Tier 0)
    - > Subsets at national centers (Tier 1)
    - > Smaller regional centers (Tier 2)
    - > Individual researchers will have copies

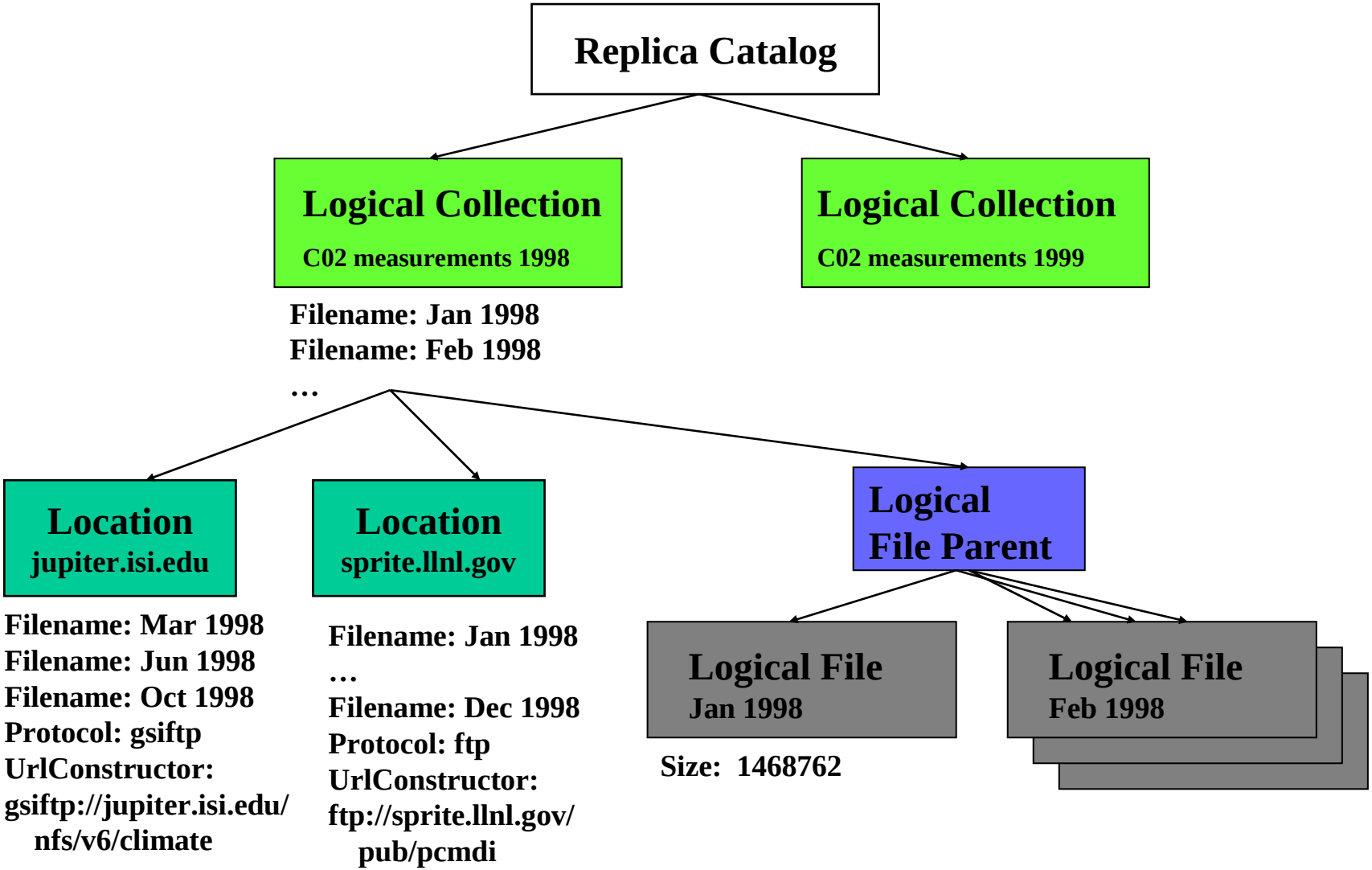
Our Approach to Replica Management

- Identify replica cataloging and reliable replication as two fundamental services
  - Layer on other Grid services: GSI, transport, information service
  - Use LDAP as catalog format and protocol, for consistency
  - Use as a building block for other tools
- Advantage
  - These services can be used in a wide variety of situations

Replica Manager Components

- Replica catalog definition
  - LDAP object classes for representing logical-to-physical mappings in an LDAP catalog
- Low-level replica catalog API
  - globus_replica_catalog library
  - Manipulates replica catalog: add, delete, etc.
- High-level reliable replication API
  - globus_replica_manager library
  - Combines calls to file transfer operations and calls to low-level API functions: create, destroy, etc.

Replica Catalog Structure: A Climate Modeling Example



Replica Catalog Services as Building Blocks: Examples

- Combine with information service to build replica selection services
  - E.g. “find best replica” using performance info from NWS and MDS
  - Use of LDAP as common protocol for info and replica services makes this easier
- Combine with application managers to build data distribution services
  - E.g., build new replicas in response to frequent accesses

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Relationship to Metadata Catalogs

- Metadata services describe data contents
  - Have defined a simple set of object classes
- Must support a variety of metadata catalogs
  - MCAT being one important example
  - Others include LDAP catalogs, HDF
- Community metadata catalogs
  - Agree on set of attributes
  - Produce names needed by replica catalog:
    - **Logical collection name**
    - **Logical file name**

Replica Catalog Directions

- Many data grid applications do *not* require tight consistency semantics
  - At any given time, you may not be able to discover all copies
  - When a new copy is made, it may not be immediately recognized as available
- Allows for much more scalable design
  - Distributed catalogs: local catalogs which maintain their own LFN -> PFN mapping
  - Soft-state updates as basis for building various configurations of global catalogs

Data Transfer APIs

- The globus_ftp_control API provides access to low-level GridFTP control and data channel operations.
- The globus_ftp_client API provides typical GridFTP client operations.
- The globus_gass_copy API provides the ability to start and manage multiple data transfers using GridFTP, HTTP, local file, and memory operations.
  - The globus-url-copy program is a thin wrapper around this API

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Replica Management APIs

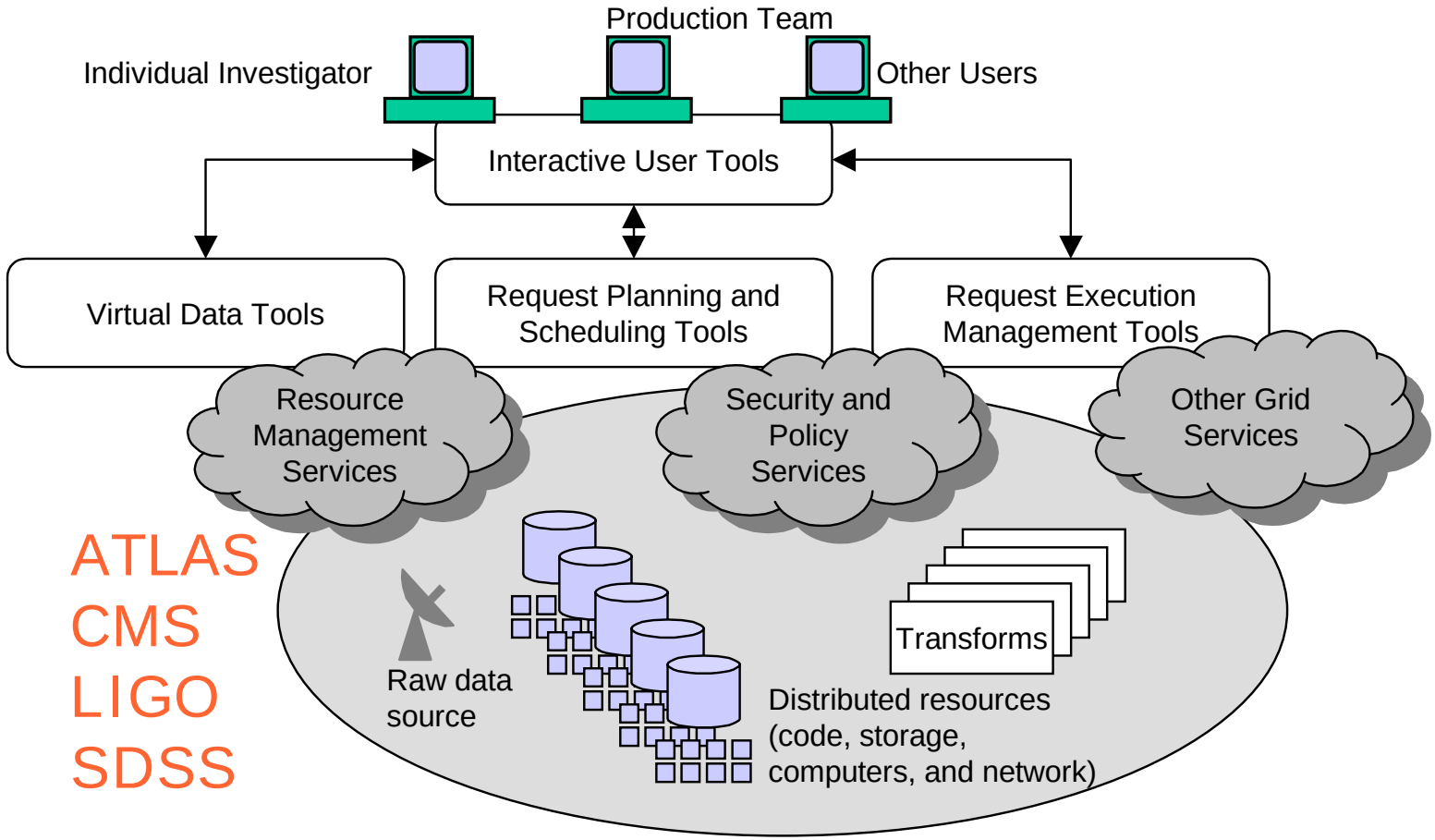
- The globus_replica_catalog API provides basic Replica Catalog operations.
- The globus_replica_management API (under development) combines GridFTP and the Replica Catalog to manage replicated datasets.

Future Directions

- Continued enhancement & standardization of protocol
  - Globus Toolkit libraries provide reference implementation
- Continue building on libraries
  - Striped server w/ server side processing
  - Reliable replica/copy management service
  - Proxies for firewalls & load balancing
- Work with more application communities

Grid Physics Network (GriPhyN)

Enabling R&D for advanced data grid systems, focusing in particular on Virtual Data concept

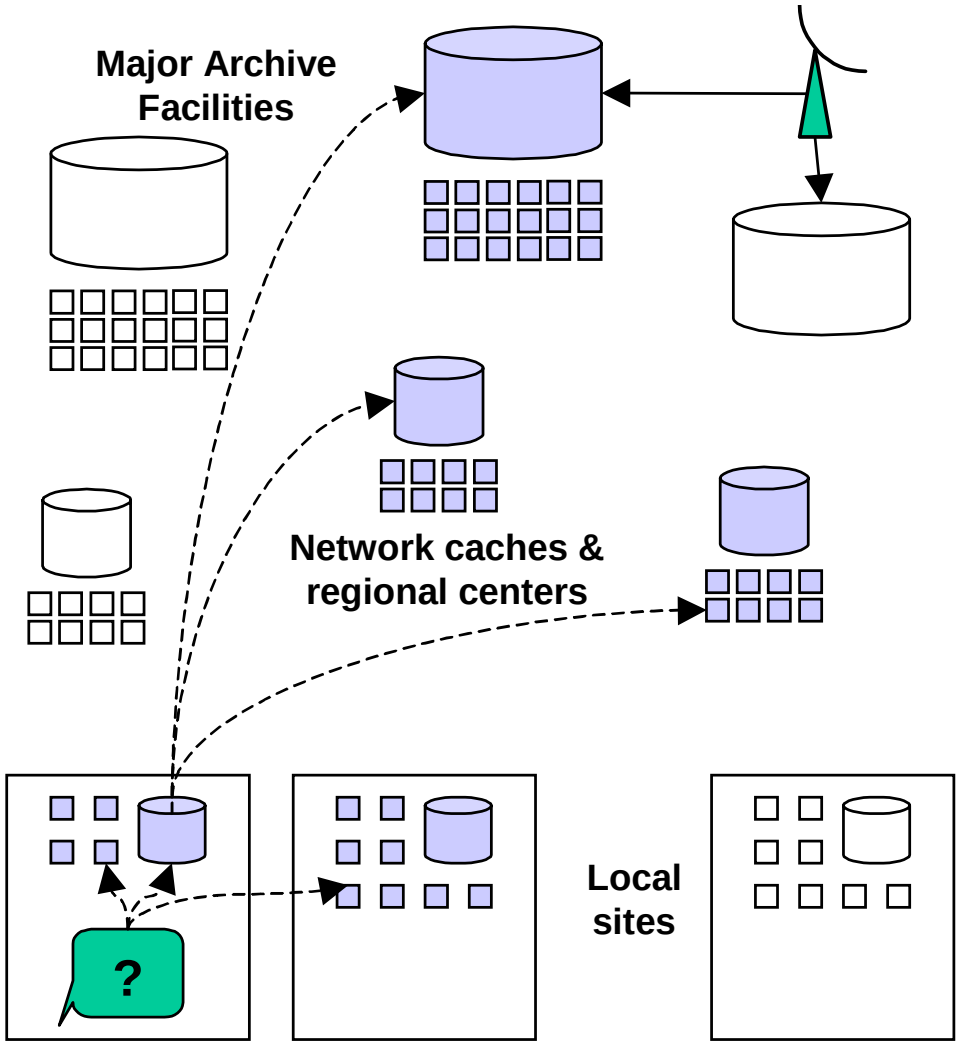


The Virtual Data Concept

"[a virtual data grid enables] the definition and delivery of a potentially unlimited virtual space of data products derived from other data. In this virtual space, requests can be satisfied via direct retrieval of materialized products and/or computation, with local and global resource management, policy, and security constraints determining the strategy used."

Virtual Data in Action

- Data request may
  - Access local data
  - Compute locally
  - Compute remotely
  - Access remote data
- Scheduling subject to local & global policies
- Local autonomy



The Globus Toolkit™:
Information Services

Grid Information Services

- System information is critical to operation of the grid and construction of applications
  - What resources are available?
    - > Resource discovery
  - What is the “state” of the grid?
    - > Resource selection
  - How to optimize resource use
    - > Application configuration and adaptation?
- We need a general information infrastructure to answer these questions

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Examples of Useful Information

- Characteristics of a compute resource
  - IP address, software available, system administrator, networks connected to, OS version, load
- Characteristics of a network
  - Bandwidth and latency, protocols, logical topology
- Characteristics of the Globus infrastructure
  - Hosts, resource managers

Grid Information: Facts of Life

- Information is always old
  - Time of flight, changing system state
  - Need to provide quality metrics
- Distributed state hard to obtain
  - Complexity of global snapshot
- Component will fail
- Scalability and overhead
- Many different usage scenarios
  - Heterogeneous policy, different information organizations, different queries, etc.

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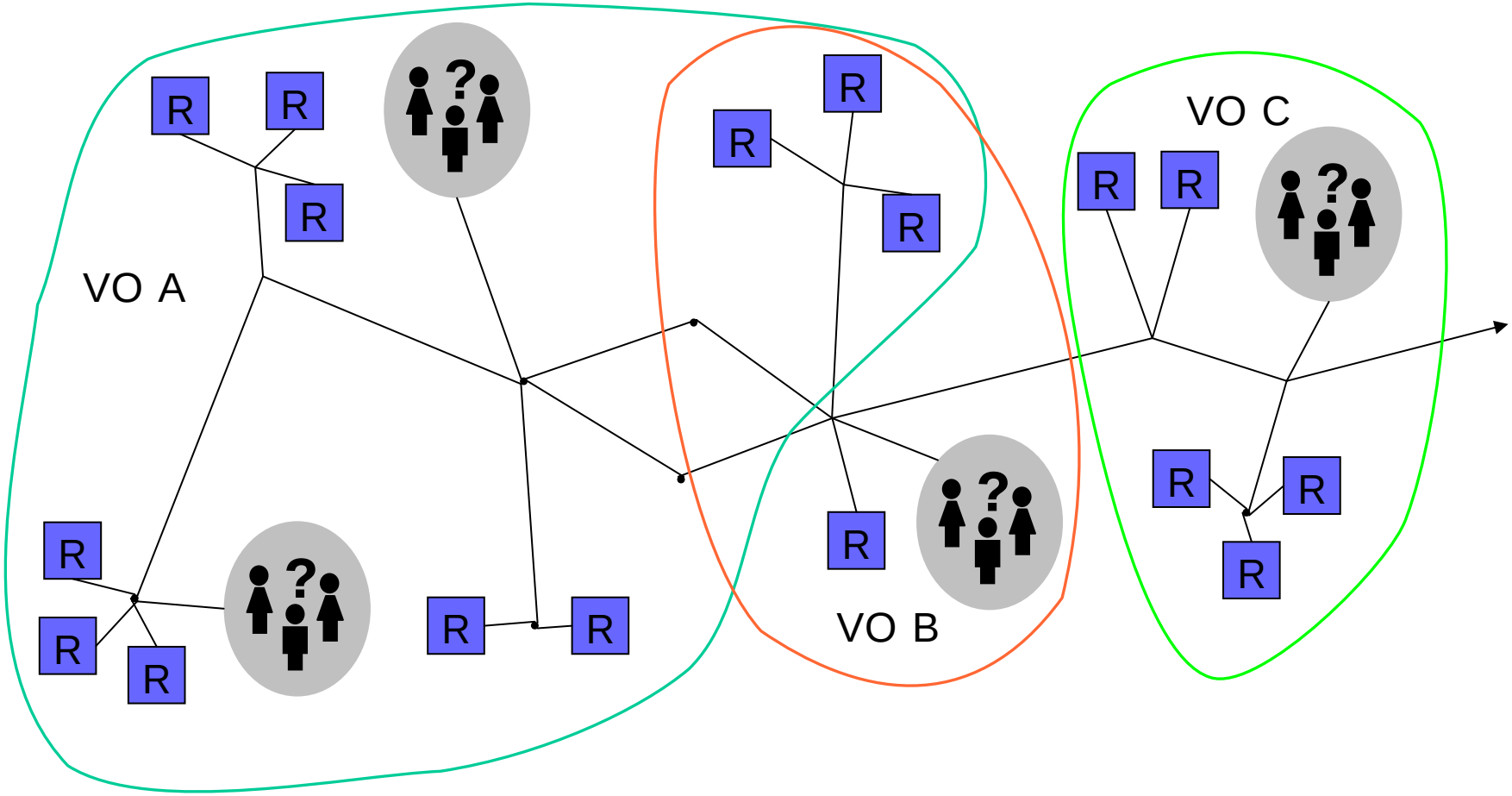
Grid Information Service

- Provide access to static and dynamic information regarding system components
- A basis for configuration and adaptation in heterogeneous, dynamic environments
- Requirements and characteristics
  - Uniform, flexible access to information
  - Scalable, efficient access to dynamic data
  - Access to multiple information sources
  - Decentralized maintenance

The GIS Problem: Many Information Sources, Many Views



What is a Virtual Organization?

- Facilitates the workflow of a group of users across multiple domains who share (some of) their resources to solve particular classes of problems
- Collates and presents information about these resources in a uniform view

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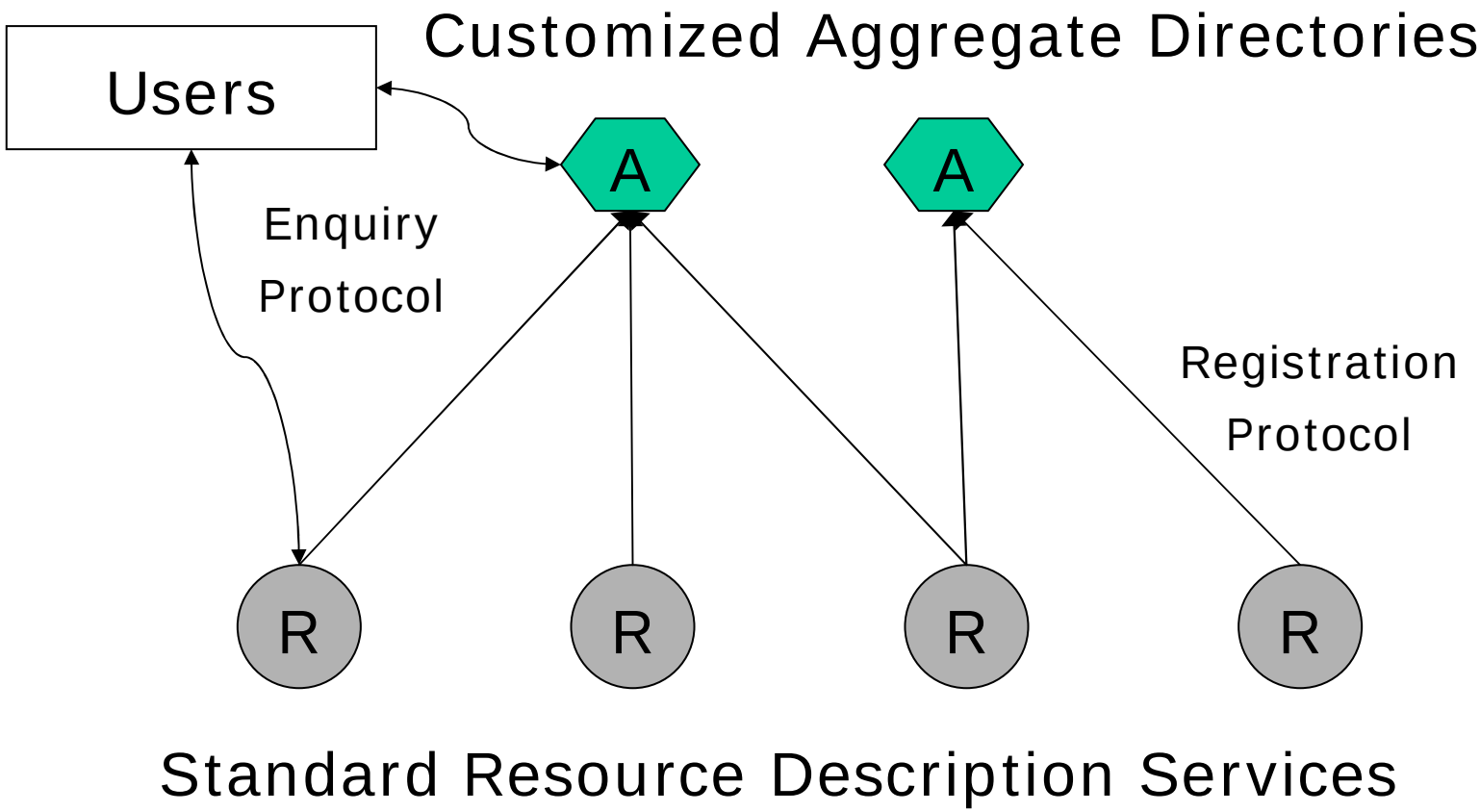
Two Classes Of Information Servers

- Resource Description Services
  - Supplies information about a specific resource (e.g. Globus 1.1.3 GRIS).
- Aggregate Directory Services
  - Supplies collection of information which was gathered from multiple GRIS servers (e.g. Globus 1.1.3 GIIS).
  - Customized naming and indexing

Information Protocols

- Grid Resource Registration Protocol
  - Support information/resource discovery
  - Designed to support machine/network failure
- Grid Resource Inquiry Protocol
  - Query resource description server for information
  - Query aggregate server for information
  - LDAP V3.0 in Globus 1.1.3

GIS Architecture



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Metacomputing Directory Service

- Use LDAP as Inquiry
- Access information in a distributed directory
  - Directory represented by collection of LDAP servers
  - Each server optimized for particular function
- Directory can be updated by:
  - Information providers and tools
  - Applications (i.e., users)
  - Backend tools which generate info on demand
- Information dynamically available to tools and applications

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Two Classes Of MDS Servers

- Grid Resource Information Service (GRIS)
  - Supplies information about a specific resource
  - Configurable to support multiple information providers
  - LDAP as inquiry protocol
- Grid Index Information Service (GIIS)
  - Supplies collection of information which was gathered from multiple GRIS servers
  - Supports efficient queries against information which is spread across multiple GRIS server
  - LDAP as inquiry protocol

LDAP Details

- Lightweight Directory Access Protocol
  - IETF Standard
  - Stripped down version of X.500 DAP protocol
  - Supports distributed storage/access (referrals)
  - Supports authentication and access control
- Defines:
  - Network protocol for accessing directory contents
  - Information model defining form of information
  - Namespace defining how information is referenced and organized

MDS Components

- LDAP 3.0 Protocol Engine
  - Based on OpenLDAP with custom backend
  - Integrated caching
- Information providers
  - Delivers resource information to backend
- APIs for accessing & updating MDS contents
  - C, Java, PERL (LDAP API, JNDI)
- Various tools for manipulating MDS contents
  - Command line tools, Shell scripts & GUIs

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Grid Resource Information Service

- Server which runs on each resource
  - Given the resource DNS name, you can find the GRIS server (well known port = 2135)
- Provides resource specific information
  - Much of this information may be dynamic
    - > Load, process information, storage information, etc.
    - > GRIS gathers this information on demand
- "White pages" lookup of resource information
  - Ex: How much memory does machine have?
- "Yellow pages" lookup of resource options
  - Ex: Which queues on machine allows large jobs?

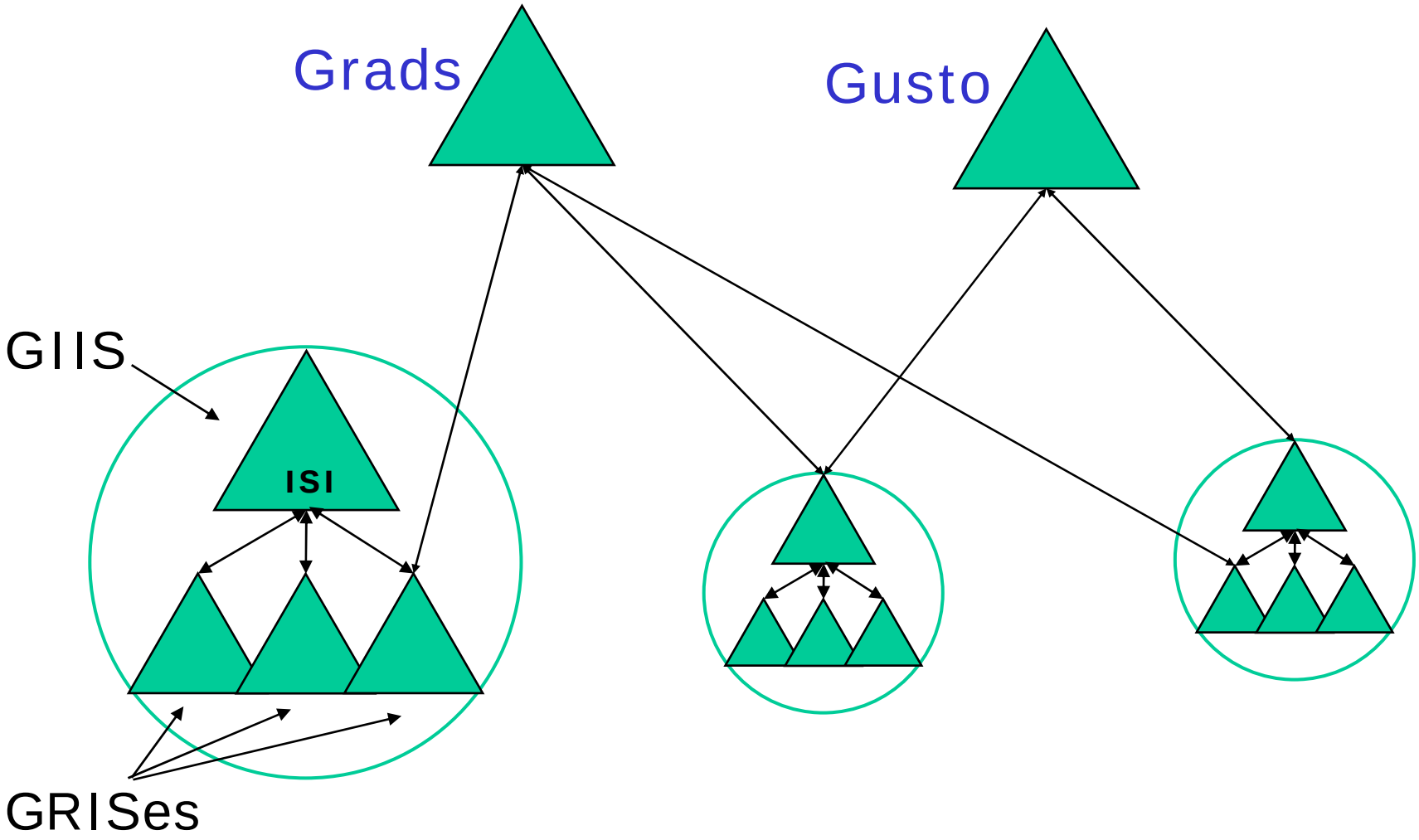
Grid Index Information Service

- GIIS describes a class of servers
  - Gathers information from multiple GRIS servers
  - Each GIIS is optimized for particular queries
    - Ex1: Which Alliance machines are >16 process SGIs?
    - Ex2: Which Alliance storage servers have >100Mbps bandwidth to host X?
  - Akin to web search engines
- Organization GIIS
  - The Globus Toolkit ships with one GIIS
  - Caches GRIS info with long update frequency
    - Useful for queries across an organization that rely on relatively static information (Ex1 above)
- Can be merged into GRIS

Finding a GRIS and Server Registration

- A GRIS or GIIS server can be configured to (de-) register itself during startup/shutdown
  - Targets specified in configuration file
- Softstate registration protocol
  - Good behavior in case of failure
- Allows for federations of information servers
  - E.g. Argonne GRIS can register with both Alliance and DOE GIIS servers

Logical MDS Deployment



MDS Commands

- LDAP defines a set of standard commands

  ldapsearch, etc.
- We also define MDS-specific commands
  - grid-info-search, grid-info-host-search
- APIs are defined for C, Java, etc.
  - C: OpenLDAP client API
    - ldap_search_s(), …
  - Java: JNDI

Information Services API

- RFC 1823 defines an IETF draft standard client API for accessing LDAP databases
  - Connect to server
  - Pose query which returns data structures contains sets of object classes and attributes
  - Functions to walk these data structures
- Globus does not provide an LDAP API. We recommend the use of OpenLDAP, an open source implementation of RFC 1823.
- LDAP APIs available in other languages
  - E.g. Java JDNI, Perl, Python, etc.

Searching an LDAP Directory

grid-info-search [options] filter [attributes]

- Default grid-info-search options
  - -h mds.globus.org — *MDS server*
  - -p 389 — *MDS port*
  - -b “o=Grid” — *search start point*
  - -T 30 — *LDAP query timeout*
  - -s **sub** — scope = subtree
    - *alternatives:*
      - **base** : *lookup this entry*
      - **one** : *lookup immediate children*

Searching a GRIS Server

grid-info-host-search [options] filter [attributes]

- Exactly like grid-info-search, except defaults:
  - -h localhost — *GRIS server*
  - -p 2135 — *GRIS port*

- Example:

  grid-info-host-search –h pitcairn “dn=*” dn

Filtering

- Filters allow selection of object based on relational operators (=, ~=,<=, >=)
  - grid-info-search “cputype=*”
- Compound filters can be construct with Boolean operations: (&, |, !)
  - grid-info-search “(&(cputype=*)(cpuload1<=1.0))”
  - grid-info-search “(&(hn~=sdsc.edu)(latency<=10))”
- Hints:
  - white space is significant
  - use -L for LDIF format

Example: Filtering

```
% grid-info-host-search -L “(objectclass=GlobusSoftware)”

dn: sw=Globus, hn=pitcairn.mcs.anl.gov, dc=mcs, dc=anl, dc=gov,
o=Grid
objectclass: GlobusSoftware
releasedate: 2000/04/11 19:48:29
releasemajor: 1
releaseminor: 1
releasepatch: 3
releasebeta: 11
lastupdate: Sun Apr 30 19:28:19 GMT 2000
objectname: sw=Globus, hn=pitcairn.mcs.anl.gov, dc=mcs, dc=anl,
dc=gov, o=Grid
```

Example: Attribute Selection

% grid-info-host- search -L “(objectclass=*)” dn hn

- Returns the distinguished name (dn) and hostname (hn) of all objects

```
dn: sw=Globus, hn=pitcairn.mcs.anl.gov, dc=mcs, dc=anl, dc=gov, o=Grid

dn: hn=pitcairn.mcs.anl.gov, dc=mcs, dc=anl, dc=gov, o=Grid
hn: pitcairn.mcs.anl.gov

dn: service=jobmanager, hn=pitcairn.mcs.anl.gov, dc=mcs, dc=anl, dc=gov, o=Grid
hn: pitcairn.mcs.anl.gov

dn: queue=default, service=jobmanager, hn=pitcairn.mcs.anl.gov, dc=mcs, dc=anl,
    dc=gov, o=Grid
```

- Objects without hn fields are still listed
- DNs are always listed

Example: Discovering CPU Load

- Retrieve CPU load fields of compute resources

% **grid-info-search -L "(objectclass=GlobusComputeResource)" **
dn cpuload1 cpuload5 cpuload15

```
dn: hn=lemon.mcs.anl.gov, ou=MCS, o=Argonne National Laboratory,
  o=Globus, c=US
cpuload1: 0.48
cpuload5: 0.20
cpuload15: 0.03

dn: hn=tuva.mcs.anl.gov, ou=MCS, o=Argonne National Laboratory,
 o=Globus, c=US
cpuload1: 3.11
cpuload5: 2.64
cpuload15: 2.57
```

The Globus Toolkit™:
Futures & Conclusions

Problem Evolution

- Past-present: O(10^2) high-end systems; Mb/s networks; centralized (or entirely local) control
  - I-WAY (1995): 17 sites, week-long; 155 Mb/s
  - GUSTO (1998): 80 sites, long-term experiment
  - NASA IPG, NSF NTG: O(10) sites, production
- Present: O(10^4-10^6) data systems, computers; Gb/s networks; scaling, decentralized control
  - Scalable resource discovery; restricted delegation; community policy; Data Grid: 100s of sites, O(10^4) computers; complex policies
- Future: O(10^6-10^9) data, sensors, computers; Tb/s networks; highly flexible policy, control

The Future: All Software is Network-Centric

- We don't build or buy "computers" anymore, we borrow or lease required resources
  - When I walk into a room, need to solve a problem, need to communicate
- A "computer" is a dynamically, often collaboratively constructed collection of processors, data sources, sensors, networks
  - Similar observations apply for software

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And Thus ...

- Reduced barriers to access mean that we do much more computing, and more interesting computing, than today => Many more components (& services); massive parallelism
- All resources are owned by others => Sharing (for fun or profit) is fundamental; trust, policy, negotiation, payment
- All computing is performed on unfamiliar systems => Dynamic behaviors, discovery, adaptivity, failure

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Summary

- The Grid problem: Resource sharing & coordinated problem solving in dynamic, multi-institutional virtual organizations
- Grid architecture emphasizes *systems problem*
  - Protocols & services, to facilitate interoperability and shared infrastructure services
- Globus Toolkit™: APIs, SDKs, and tools which implement Grid protocols & services
  - Provides basic software infrastructure for suite of tools addressing the *programming problem*