Object Databases as Data Stores for HEP

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The RD45 Project

- Started in 1995 to find solutions to problems of **LHC data management**
  - Enormous data volumes & rates, project lifetime
- Proposed solutions being adopted by **current** experiments
  - **Objectivity/DB** & HPSS
- In 1999, several experiments will start storing ~200-400TB/year at upto 35MB/second
- Similar problem to LHC, but **today!**

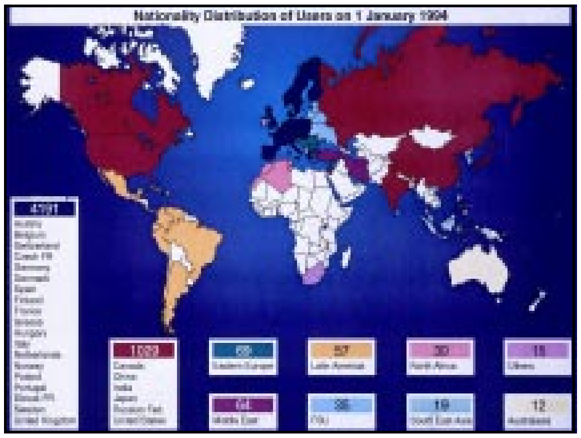
High Energy Physics

- Study of **fundamental constituents** of matter and **forces** between them
  - quarks, electrons, neutrinos, photon, Z^0, $W^\pm$, etc.
  - Higher and higher energies are required to delve deeper and deeper into matter
- i.e. larger, more powerful, more expensive
  - No longer affordable by individual countries

CERN

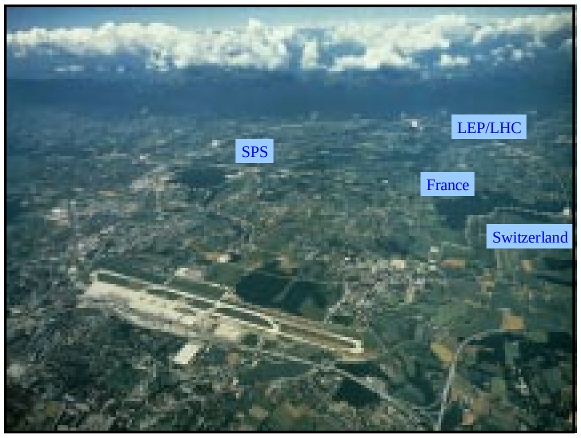
- Conseil Europeen pour la Recherche Nucleaire
- Established in 1954
  - **"kickstart"** research in Europe
- Currently funded by 19 European Countries
- Next main research program:

  Large **H**adron **C**ollider
- Startup: **2005**, data taking **~20** years



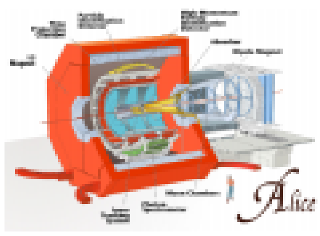
LEP Characteristics

- Circumference of the accelerator: 26.659 km
- Depth of the tunnel housing LEP: -50 to -175 m
- Alignment accuracy : 0.1 mm
- Speed of e^+e^- : 0.035 km/h below light speed
  - over 11200 cycles / second
- LEP can detect:
  - the orbit of the moon,
  - heavy rainfall,
  - changing water levels in Lake Geneva,
  - the Geneva-Paris TGV.
- LHC will collide protons in the same tunnel



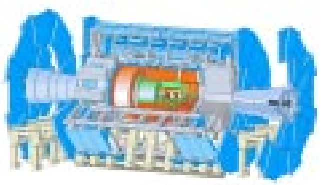
ALICE

- Heavy ion experiment at LHC
- Studying ultra-relativistic nuclear collisions
- Relatively short running period
  - online 1 month/year
  - 1 PB/month
- Extremely high data rates
  - 1.5GB/s



ATLAS

- General-purpose LHC experiment
- High Data rates:
  - 100MB/second
- High Data volume
  - 1PB/year
- Test beam projects using Objectivity/DB in preparation:
  - Calibration database
  - Expect 600GB raw and analysis data

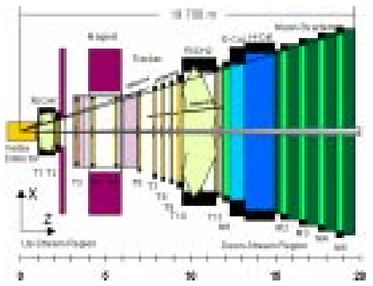


CMS

- General-purpose LHC experiment
- Data rates of 100MB/second
- Data volume of 1PB/year
- Two test beams projects based on Objectivity successfully completed.
- Database used in the complete chain: Test beam DAQ, Re-construction and Analysis

LHCb

- Dedicated experiment looking for CP-violation in the B-meson system.
- Lower data rates than other LHC experiments.
- Total data volume around 400TB/year.



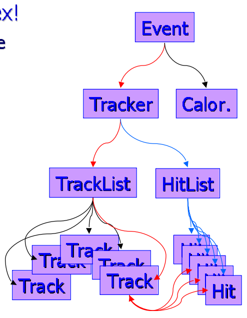
The Large Hadron Collider

- Currently under construction: data ~2005
- 4 large "experiments", run for ~20 years
  - ~2000 people, ~200 institutes, ~20 countries

Time interval	ATLAS/CMS	ALICE
1 second	100 MB	1.6 GB
1 minute	6 GB	100 GB
1 hour	360 GB	6 TB
1 day	8.6 TB	140 TB
1 week	60 TB	1 PB
1 month	260 TB	
1 year (100 days)	**1 PB**	
Total LHC (20 yrs)	**100 PB**	

HEP Data Models

- HEP data models are complex!
  - Typically hundreds of structure types (classes)
  - Many relations between them
  - Different access patterns
- LHC experiments rely on OO technology
  - OO applications deal with networks of objects
  - Pointers (or references) are used to describe relations



Data Management at LHC

- LHC experiments will store huge data amounts
  - 1 PB of data per experiment and year
  - 100 PB over the whole lifetime
- Distributed, heterogeneous environment
  - Some 100 institutes distributed world-wide
  - (Nearly) any available hardware platform
  - Data at regional-centers?
- Existing solutions do not scale
  - Solution suggested by RD45: ODBMS coupled to a Mass Storage System
    - e.g. Objectivity/DB coupled to HPSS

Features of HEP Data

☺Data is essentially read-only
☺Small number of concurrent users (1-100)
☺Very low transaction rate
☺Can accept data loss(!)

💣Data volumes and rates (up to 100PB, 1.5GB/s)
💣Fully distributed
💣Project Lifetime (~25 years)

Physics Data Processing Tasks

- **Reconstruction:**
  - support multiple writers (**100-500** filter farm cpu's)
  - support aggregate data rates sufficient to keep up with acquisition
  - **100MB/s** for ATLAS/CMS; **1.5GB/s** for ALICE
- **Analysis:**
  - support multiple readers (~**150** "effective" users)
  - data volumes and rates hard to predict at this time
  - assume aggregate data rates ≤ reconstruction
- **Simulation:**
  - Very CPU intensive process
  - No "special" requirements
  - Sufficient to satisfy requirements of reconstruction and analysis

Reconstruction

- During past 3 years, NA45 have performed several **production** reconstruction runs using Objectivity/DB
  - initially on the Meiko CS-2 (HyperSparc SMP)
  - ported to NT, writing with 16MB/sec
- New **production** schedule now
  - reprocessing of existing data
  - DAQ tests with new TPC and 16MB/sec Rate
- **Production** demonstration of parallel writing into ODBMS
- **Production** demonstrations also made in CMS Test Beams
- Data Volumes in **10-100GB** range

The RD45 Collaboration

- ANL: D. Malon
- BNL: M. Purschke
- Caltech: J. Bunn, H. Newman, R. Wilkinson
- DESY: M. Gasthuber
- U. Heidelberg: A. Pfeiffer
- LBNL: D. Quarrie
- KEK: Y. Morita
- Krakow: S. Jagielski
- MIT: A. Klimentov
- Orsay: C. Arnault, A. Schaffer
- SLAC: J. Becla, G. Cosmo
- TATA: S. Banerjee
- Tufts: S. Rolli, K. Sliwa
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  I. Willers

Project Stages

❶ Develop complete list of requirements, evaluate existing packages, limited prototyping (~6 months)
  - March - November 1995
  - Interim Review November 1995

❷ Detailed prototyping and evaluation, prototype applications, comparisons with established metrics etc.
  - November 1995 - April 1998
  - Reviews in Spring 1996, 1997 & 1998

❸ Implementation phase
  - May 1998+
  - Production Services, Outstanding R&D Issues

Why an ODBMS?

- Key requirements could not be met by language extensions, light-weight object managers
- Strong requirement for consistent interface
  - "The ODMG language bindings are based on one fundamental principle: the programmer should perceive the binding as a single language for expressing both database and programming operations, not two separate languages with arbitrary boundaries between them."

☺ Use of an Objectivity/DB federation met our main requirements
  - Enhancements required but (apparently) sufficient flexibility in architecture to accommodate these

Object Persistency

- Persistency
  - Objects retain their state between two program contexts
- Storage entity is a complete object
  - State of all data members
  - Object class
- OO Language Support
  - Abstraction
  - Inheritance
  - Polymorphism
  - Parameterised Types (Templates)

OO Language Binding

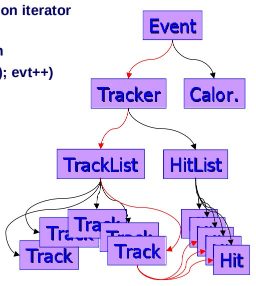
- User has to deal with copying between program and I/O representations of the same data
  - User has to traverse the in-memory structure
  - User has to write and maintain specialised code for I/O of each new class/structure type
- Tight Language Binding
  - ODBMS allow to use persistent objects directly as variables of the OO language
  - C++, Java and Smalltalk (heterogeneity)
- I/O on demand
  - No explicit store & retrieve calls

A Code Example

```
Collection<Event> events;          // an event collection
Collection<Event>::iterator evt;  // a collection iterator

// loop over all events in the input collection
for(evt = events.begin();  evt != events.end(); evt++)
    {
    // access the first track in the tracklist
    d_Ref<Track> aTrack;
    aTrack  = evt->tracker->trackList[0];

    // print the charge of all its hits
    for (int i = 0; i < aTrack->hits.size(); i++)
          cout  << aTrack->hits[i]->charge
                  << endl;
    }
```

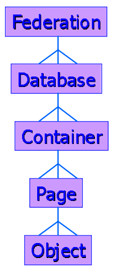


Concurrent Access

- Support for multiple concurrent writers
  - e.g. Multiple parallel data streams
  - e.g. Filter or reconstruction farms
  - e.g. Distributed simulation
- Data changes are part of a Transaction
  - ACID: Atomic, Consistent, Isolated, Durable
- Access is co-ordinated by a lock server
  - MROW: Multiple Reader, One Writer per container (Objectivity/DB)

Objectivity/DB Architecture

- Architectural Limitations: OID size 8 bytes
- 64K databases
- 32K containers per database
- 64K logical pages per container
  - 4GB containers for 64kB page size
  - 0.5GB containers for 8kB page size
- 64K object slots per page
- Theoretical limit: 10 000PB
  - assuming database files of 128TB
- RD45 model assumes 6.5PB
  - assuming database files of 100GB
  - extension or re-mapping of OID have been requested



Scalability Tests

- Created federations of **1TB**
  - limited by available disk space ($$$)
  - A 1TB federation requires only **40** DBs of **25GB** each!
- Created federations up to limit of **2^{16}** databases
- Tested individual databases up to **25GB**
  - database size “limited” by filesystem
  - practical limits (network, staging) suggest 1-10GB maximum size
- Numerous production federations of **10-100GB**
  - > 1k databases
- Plans for 1999 include several federations of **100TB+**
- Enhancement requests for scalability up to 100PB+
  - multi-file databases

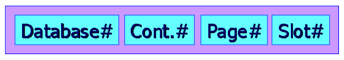
Scalability Tests II

- LHC Experiments predict some **150** “effective simultaneous interactive users”
  - e.g. **20** analysis groups, each with **10-30** members
- Can an ODBMS support ~**150** concurrent analyses?
- A simulation was performed on the Caltech Exemplar
  - 1/3 clients read objects **10KB** in size; compute **0.001s** per object
  - 1/3 clients read objects **100KB** in size; compute **0.1s** per object
  - 1/3 clients read objects **500KB** in size; compute **10s** per object
- Simulation showed no degradation in performance with up to **150** concurrent analyses

☺ **150** effective simultaneous users achievable today

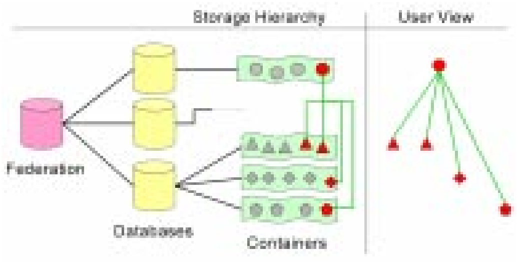
- *Without* using DB partitions, replication etc.

Navigational Access



- Unique Object Identifier (OID) per object
  - Direct access to any object in the distributed store
  - Natural extension of the pointer concept
- OIDs allow to implement networks of persistent objects (“associations”)
  - Cardinality: 1:1 , 1:n, n:m
  - uni- or bi-directional (referential integrity!)
- Transparent use of OIDs through “smart-pointers”

Physical Model and Logical Model



- Physical model may be changed to optimise performance
- Existing applications continue to work

Page Server & Container Locking

- Objectivity/DB
  - Page exchange between client and server
    - Page does contain not only requested data
    - In case of good clustering, it contains other objects that will be requested soon
  - Server only "knows" about I/O pages
    - Thin server, fat client
    - Improved scalability
  - Locking on container level
    - All objects in one container are locked at once
    - Improved scalability and performance

Object Clustering

- Goal: Transfer only "useful" data
  - from disk (page) server to client cache
  - from tape to disk
- Physically cluster objects according to main access patterns
  - Clustering by type
    - e.g. Track objects are "always" accessed with their Hits
- Main access patterns may change over time
  - Performance may profit from re-clustering
  - Clustering of individual objects
    - e.g. All Higgs events should reside in one file
  - first studies on automatic reclustering

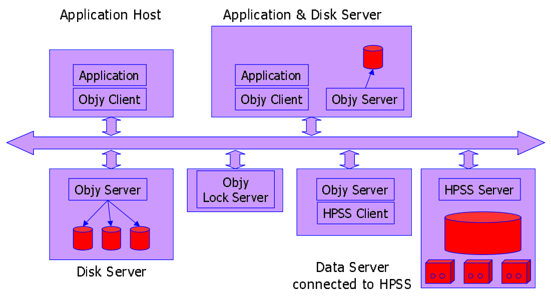
Clustering on a Larger Scale

- Objectivity limits containers to 64k logical pages
  - about 0.5 GB for 8kB page size

  Simple strategy:
  - check container size when a new object is created
  - create a new container if the current one approaches the limit
  - manage a ***persistent*** list of containers
- Objectivity locks on container level
  - Avoid lock contention in multi-processor environments

  Simple strategy:
  - assign one container per process
  - manage the list of containers as one logical container

A Distributed Federation

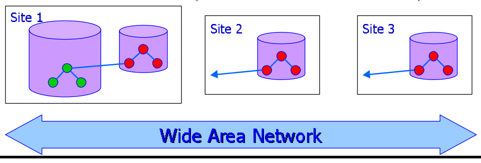


Mass Storage Interface

- Clear from early days of RD45 that an interface to an MSS was required
  - cannot assume that multi-PB disk farms will be affordable and/or manageable
- **HPSS** has emerged as the "MSS of choice" in the HEP community
- An evaluation of Objectivity/DB and HPSS architectures suggested that most appropriate interface would be between the Objectivity/DB server and HPSS client API
- A prototype of such an interface has been produced and is in test at Caltech, CERN and SLAC

Data Replication

- Objects in a replicated DB exists in all replicas
  - Multiple physical copies of the same object
  - Copies are kept in sync by the database
- Enhance performance
  - Clients access a local copy of the data
- Enhance availability
  - Disconnected sites may continue to work on a local replica



Why Replicate?

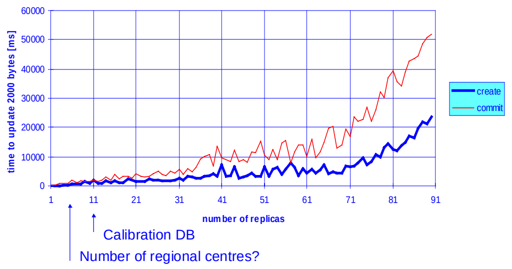
- Increased fault tolerance
  - critical resources are duplicated in more than one location
  - users can continue to work even if WAN is down or one "image" unavailable
- Increased performance
  - access to frequently used objects can be satisfied from a local replica, avoiding WAN network traffic

- Data Collection
  - e.g. "centralisation" of simulated events generated at outside institutes
- Data Distribution
  - tag objects, analysis objects, calibration & production data
- ❶ Calibration Data
  - typically "replicated" to ~10 outside institutes (cf HEPDB)
- ❷ Analysis Data
  - Use ODBMS to maintain coherent "copies" at regional centres

Replication Tests

- Previous tests of replication, based on a pre-release, were limited to NT and the LAN
- Have now extended these tests to NT(Alpha, Intel) + Unix (DEC, HP, IBM, SGI, Sun), large numbers of images (100), and the WAN (CERN-Caltech)
- Replication functions correctly in these environments
- Need appropriate network bandwidth
- Need to understand when replication is appropriate
  - calibration databases, tag databases, collections etc.
- Enhancement requests include "tape replication"
  - need also increased reliability & bug fixes (V5?)

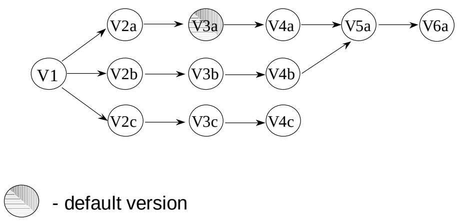
Replication With Many Images



Replication: Problems

- Main problem concerns Fault Tolerant Option (FTO)
  - ***All*** partitions must be online for catalog and/or schema changes
  - Rules out production use
  - Plans to use DRO quorum mechanism in V6(?)
- Outstanding enhancement request to permit "offline" (e.g. tape) replication
  - for bulk data transfer
- Outstanding choice of "best" remote image
  - e.g. images at srv1.cern.ch, srv1.fnal.gov
  - Where does an application on usr1.cern.ch read from?
  - What about usr1.anl.gov?

Object Versioning


$$\begin{tikzcd}
 & V2a \arrow[r] & V3a \arrow[r] & V4a \arrow[r] & V5a \arrow[r] & V6a \\
V1 \arrow[ur] \arrow[r] \arrow[dr] & V2b \arrow[r] & V3b \arrow[r] & V4b \arrow[ur] & & \\
 & V2c \arrow[r] & V3c \arrow[r] & V4c & &
\end{tikzcd}$$

▨ - default version

- Maintain multiple versions of a single "logical" object
- Example: Versions of calibration data in the BaBar calibration DB package

The ODMG Standard

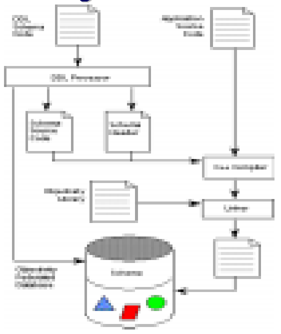
- Standardise on
  - Data definition language ODL
  - Data interchange format OIF
  - Language binding for C++, Java and SmallTalk
- Goal: Simplify code migration from one database vendor to another
  - Most frequently used API elements are covered by the ODMG 2.0 standard.
  - Performance and the feature set of different ODBMS products differs significantly !
- Any large scale migration will still require a significant effort!

DDL Restrictions

- Persistent classes may not:
  - contain other persistent classes as data members
    - They may contain references to other persistent class though
    - Late (multiple-) inheritance from d_Object helps to keep transient and persistent classes in sync
  - contain C++ pointers or references
    - Neither directly nor through embedded classes
    - replace C++ pointers by database smart pointers
- ❷ is the more intrusive change
  - **Type declarations** of pointers referencing persistent objects **have to be changed** for all clients of a persistent capable class.
  - Code that **uses** these variables stays untouched.

Schema Handling

- Definitions of persistent capable classes made in **.DDL** files
- ***ooddlx*** processor generates appropriate headers & source code
  - Schema is added to federated database
- Applications are built using generated files and the Objectivity library



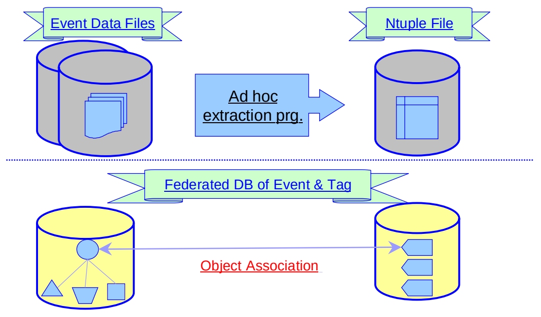
Schema Evolution

- Evolve the object model over the experiment lifetime
  - migrate existing data after schema changes
  - minimise impact on existing applications
- Supported operations
  - add, move or remove attributes within classes
  - change inheritance hierarchy
- Migration of existing Objects
  - immediate: all objects are converted using an upgrade application
  - lazy: objects are upgraded as they are accessed

Data Analysis Scenario

- Hundreds of Physicist world-wide will
  - select events based on multiple interval queries on event properties
    - multi dimensional query : O(10-100) dimensions
    - some properties are user derived
    - list of properties differs between different analysis types
    - interval definition changes frequently
  - navigate to specific detector information
    - sample and store distributions of properties
    - define and store new persistent types for their private analysis objects

Ntuple versus TagDB Model

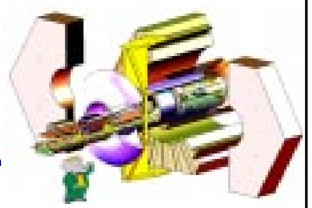


Purpose of Using Tags

- Tags are mainly used to speedup selections
  - Tag data is much better clustered than the original data
- A collection of Tags defines an Event Collection
  - in fact, tag collections are only a special case of an event collection
- Tag attributes may be visualised interactively
  - without the need to write any code
- Association to the Event may be used to navigate to any other part of the Event
  - even from an interactive visualisation program

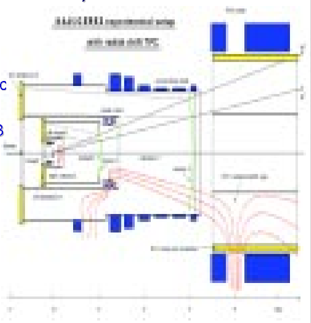
Production - BaBar

- BaBar at SLAC, due to start taking data in 1999
- Objectivity/DB is used to store event, simulation, calibration and analysis data
- Expected amount 200TB/year, majority of storage managed by HPSS
- Mock Data Challenge 2:
  - Production of 3-4 Million events in August/September
  - Partly distributed to remote institutes
- Cosmic runs starting in October



Production - CERES/NA45

- Heavy ion experiment at the SPS
- Study of e+e- pairs in relativistic nuclear collisions
- Successful use of Objectivity/DB from a reconstruction farm (32 Meiko CS2 nodes)
- Expect to write 30 TB of raw data during 30 days of data taking
- Reconstructed and filtered data will be stored using the Objectivity production service.



COMPASS

- COMPASS expects to begin full data taking in 2000 with a preliminary run in 1999.
- Some 300TB of raw data will be acquired per year at rates up to 35MB/second.
- Analysis data is expected to be stored on disk, requiring some 3-20TB of disk space.
- Some 50 concurrent users and many passes through the data are expected.
- Rely on the Objectivity production service at CERN

Summary

- ODBMS based data stores provide
  - **a single logical view** of complex object models
  - integration with **multiple OO languages**
  - support for **physical clustering** of data
  - scaling up to **PB distributed data stores**
  - seamless **integration with MSS** like HPSS
- Adopted by a large number of HEP experiments
  - even FORTRAN based experiments evaluate Objectivity/DB for analysis and data conservation
- Entering production phase at CERN now
  - Objectivity service has been set-up for ATLAS, CMS, COMPASS and NA45