

# Data Integration in Bioinformatics and Life Sciences

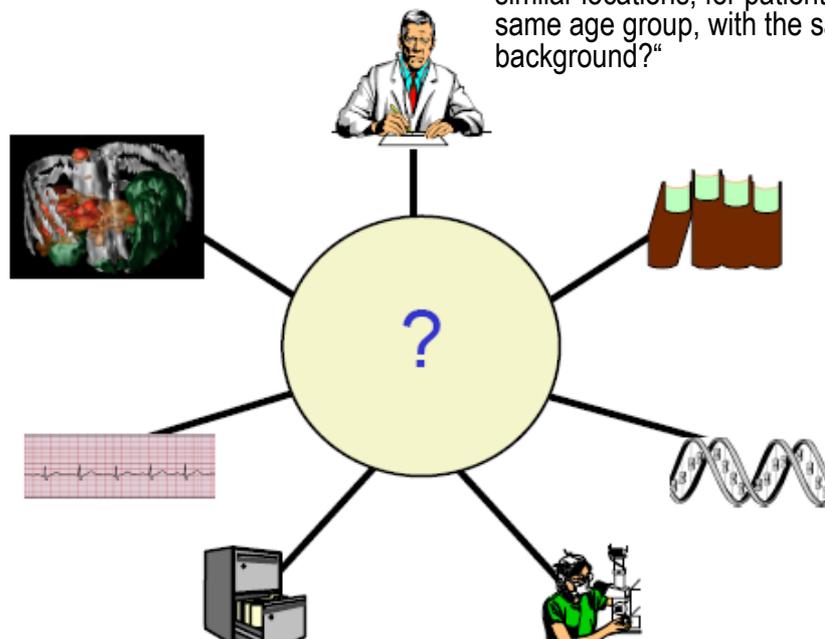
Erhard Rahm, Toralf Kirsten, Michael Hartung

<http://dbs.uni-leipzig.de>  
<http://www.izbi.de>

EDBT – Summer School, September 2007

## What is the Problem?

„What protocols were used for tumors in similar locations, for patients in the same age group, with the same genetic background?“



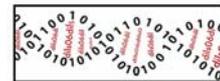
Source: L. Haas, ICDE2006 keynote

## DILS workshop series

- International workshop series  
**Data Integration in the Life Sciences (DILS)**



- DILS2004: Leipzig  
(Interdisciplinary Center for Bioinformatics)
- DILS2005: San Diego, USA  
(UCSD Supercomputing Center)
- DILS2006: Cambridge/Hinxton, UK  
(EBI)
- DILS2007: Philadelphia (UPenn)
- DILS2008: Have you ever been in Paris? 😊



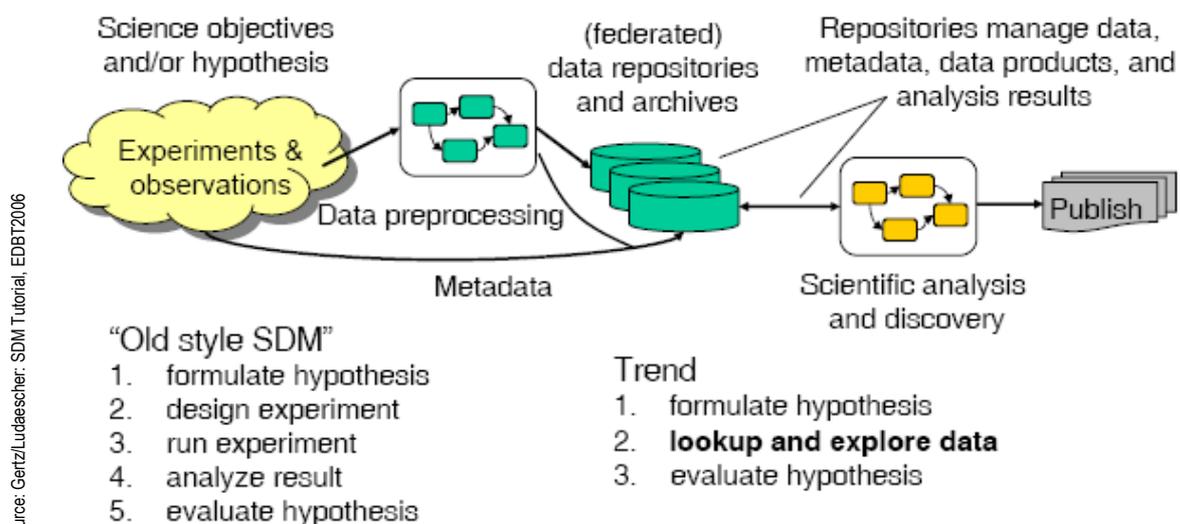
## Agenda

- Kinds of data to be integrated
- General data integration alternatives
- Warehouse approaches
- Virtual and mapping-based data integration
- Matching large life science ontologies
- Data quality aspects
- Conclusions and further challenges

# Agenda

- Kinds of data to be integrated
  - Experimental data
  - Clinical data
  - Public web data
  - Ontologies
- General data integration alternatives
- Warehouse approaches
- Virtual and mapping-based data integration
- Matching large life science ontologies
- Data quality aspects
- Conclusions and further challenges

# Scientific data management process



- Sharing/reuse of data products
- community-oriented research

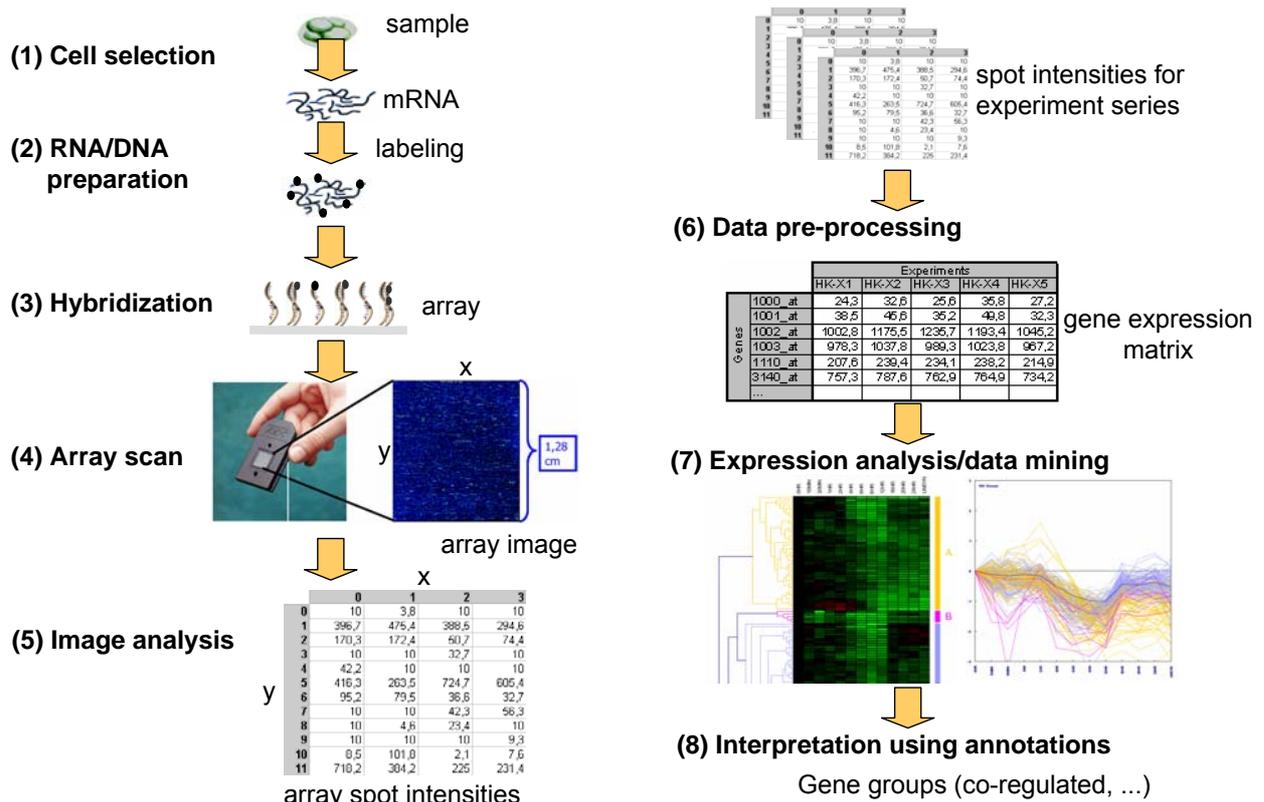
# Data integration in life sciences

- Many heterogeneous data sources
  - Experimental data produced by chip-based techniques
    - Genome-wide measurement of gene activity under different conditions (e.g., normal vs. different disease states)
  - Experimental annotations (metadata about experiments)
  - Clinical data
  - Lots of inter-connected web data sources and ontologies
    - Sequence data, annotation data, vocabularies, ...
  - Publications (knowledge in text documents)
  - Private vs. public data
  
- Different kinds of analysis
  - Gene expression analysis
  - Transcription analysis
  - Functional profiling
  - Pathway analysis and reconstruction
  - Text mining , ...



Affymetrix gene expression microarray

# Expression experiment and analysis



## Experimental data

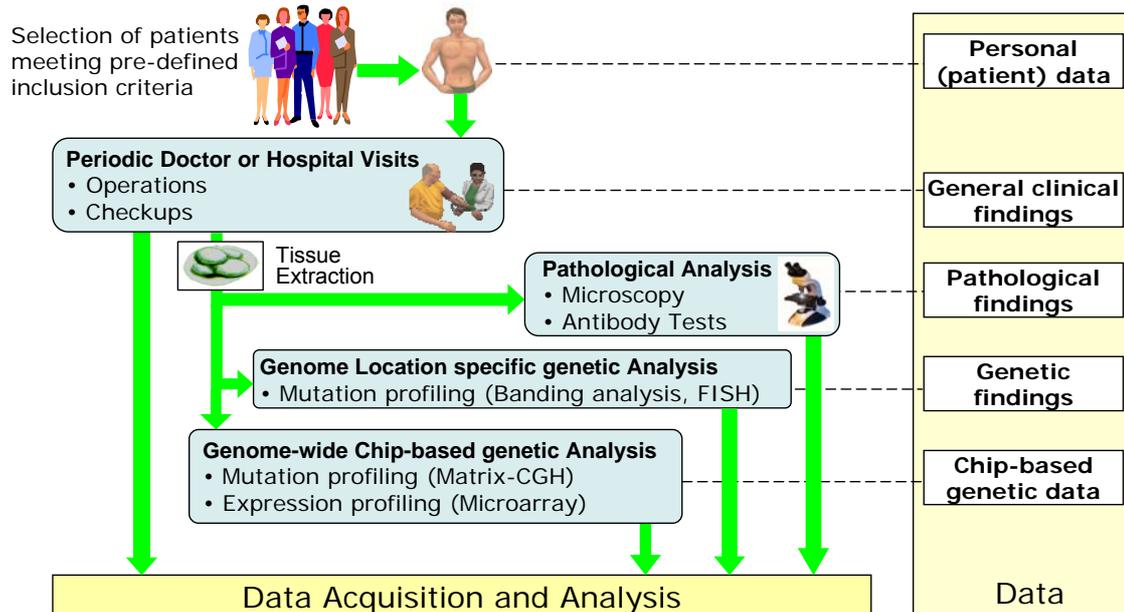
- High volume of experimental data
  - Various existing chip types for gene expression and mutation analysis
  - Fast growing amount of numeric data values
- Need to **pre-process chip data** (no standard routines)
  - Different data aggregation levels (e.g. Affy probe vs. probeset expression values)
  - Various statistical approaches, e.g. tests and resampling procedures, ...
  - Visualizations, e.g. Heatmap, M/A plot, ...
- Need for comprehensive, standardized **experimental annotations**
  - Experimental set up and procedure (hybridization process, utilized devices, ...)
  - Manual specification by the experimenter
  - Often user-dependent utilization of abbrev. and names / synonyms
  - Recommendation: **Minimal Information about a Microarray Experiment\***

\* Brazma et al.: *Minimum information about a microarray experiment (MIAME) – toward standards for microarray data.*  
Nature Genetics, 29(4): 365-371, 2001

## Clinical data: Requirements

- Patient-oriented data
  - Personal data
  - Different types of findings, e.g. general clinical findings (blood pressure, etc.), pathological findings (tissue samples), genetic findings
  - Applied therapies (timing and dosages of drugs, ...)
- Clinical studies to evaluate and improve treatment protocols, e.g. against cancer
  - Data acquisition during complex workflows running in different hospitals
  - Special software systems for study management (eResearch Network, Oracle Clinical, ...)
- **New research direction:** collect and evaluate patient-specific genetic data (e.g., gene expression data) within clinical studies to investigate molecular-biological causes of diseases and impact of drugs
- Need to integrate experimental and clinical data within distributed study management workflows
- High privacy requirements: protect identity of individual patients

# Clinical trials: Inter-organizational workflows



# Publicly accessible data in web sources

- Genome sources: Ensembl, NCBI Entrez, UCSC Genome, ...
  - Objects: Genes, transcripts, proteins etc. of different species
- Object specific sources
  - Proteins: UniProt (SwissProt, TrEMBL), Protein Data Bank, ...
  - Protein interactions: BIND, MINT, DIP, ...
  - Genes: HUGO (standardized gene symbols for human genome), MGD, ...
  - Pathways: KEGG (metabolic & regulatory pathways), GenMAPP, ...
  - ...
- Publication sources: Medline / Pubmed (>16 Mio entries)
- Ontologies
  - Utilized to describe properties of biological objects
  - Controlled vocabulary of concepts to reduce terminology variations
  - Popular examples: Gene Ontology, Open Biomedical Ontologies (OBO)

# Sample web data with cross-references

- Annotation data vs. mapping data

LocusID: 15 ← source-specific ID (accession)

Overview ?

Product: arylalkylamine N-acetyltransferase  
 Alternate Symbols: SNAT, AA-NAT  
 Alias: serotonin N-acetyltransferase } annotations: names, symbols, synonyms, etc.

Function Submit GeneRIF (All Pubs) ?

EC Number: 2.3.1.87 ← Enzyme

Gene Ontology™:  
 Term  
 ♦ acyltransferase activity  
 ♦ aralkylamine N-acetyltransferase activity } GeneOntology

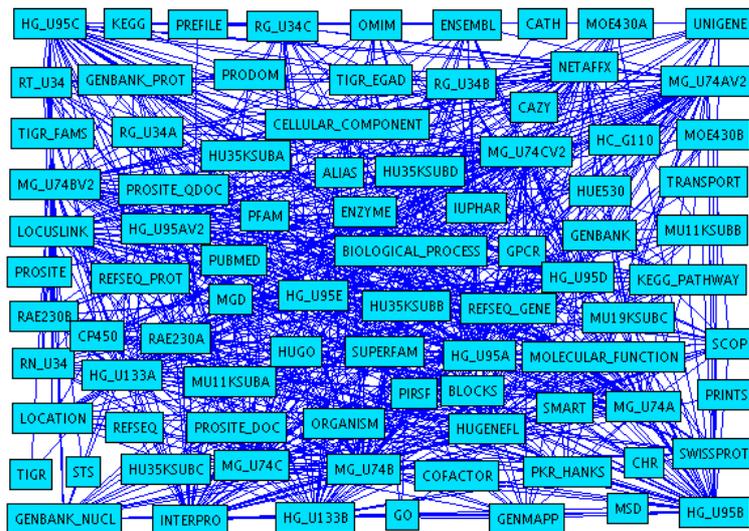
Additional Links

♦ OMIM: 600950 ← OMIM  
 ♦ UniGene: Hs.431417 ← UniGene  
 ♦ KEGG pathway: Tryptophan metabolism ← KEGG

References to other data sources

- Problem: semantics of mappings (missing mapping type)
  - Gene ↔ gene: orthologous vs. paralogous genes

# Highly connected data sources



- Many, highly connected data sources and ontologies
- Heterogeneity
  - Files and databases
  - Format and schema differences
  - Semantics
- Incomplete data sources
- Overlapping data sources
  - need to fuse corresponding objects from different sources
- Frequent changes
  - Data, schema, APIs

- common (global) database schema ???

# Ontologies

- Increasing use of ontologies in bioinformatics and medicine to organize domains, annotate data and support data integration
  - Develop a shared understanding of concepts in a domain
  - Define the terms used
  - Attach these terms to real data (annotation)
  - Provide ability to query data from different sources using a common vocabulary
- Some popular life science ontologies
  - Gene Ontology** (<http://www.geneontology.org>)
    - Species-independent, comprehensive sub-ontologies about Molecular Functions, Biological Processes and Cellular Components
  - UMLS** – Unified Medical Language System (<http://www.nlm.nih.gov/research/umls/umlsmain.html>)
    - Metathesaurus comprising medical subjects and terms of Medical Subject Headings, International Classification of Diseases (ICD), ...

# OBO – Open Biomedical Ontologies

- An umbrella project for grouping different ontologies in biological/medical field

## Why OBO?

- GO only covers three specific domains
- Other aspects could also be annotated: anatomy, ...
- No standardization of ontologies: format, syntax, ...
- What ontologies do exist in the biomedical domain?
- Creation takes a lot of work → Reuse existing ontol.

## Requirements for ontologies in OBO:

- Open, can be used by all without any constraints
- Common shared syntax
- No overlap with other ontologies in OBO
- Share a unique identifier space
- Include text definitions of their terms



The screenshot shows the OBO website homepage. At the top, there is a navigation menu with links: Main, Ontologies, Browse, Project, CVS, Subscribe, Contact. The main heading is 'OBO open biomedical ontologies'. Below this, a paragraph states: 'Open Biomedical Ontologies is an umbrella web address for well-structured controlled vocabularies for shared use across different biological and medical domains.' There are two links: 'View the OBO ontologies in table form' and 'Browse the OBO ontologies'. A section titled 'OBO Inclusion Criteria' follows, containing three numbered points: 1. The ontologies must be open and can be used by all without any constraint other than that their origin must be acknowledged and they cannot be altered and redistributed under the same name. 2. The ontologies are in, or can be instantiated in, a common shared syntax. This may be either the GO syntax, extensions of this syntax, or OWL. 3. The ontologies are orthogonal to other ontologies already lodged within OBO.

## Currently covered aspects:

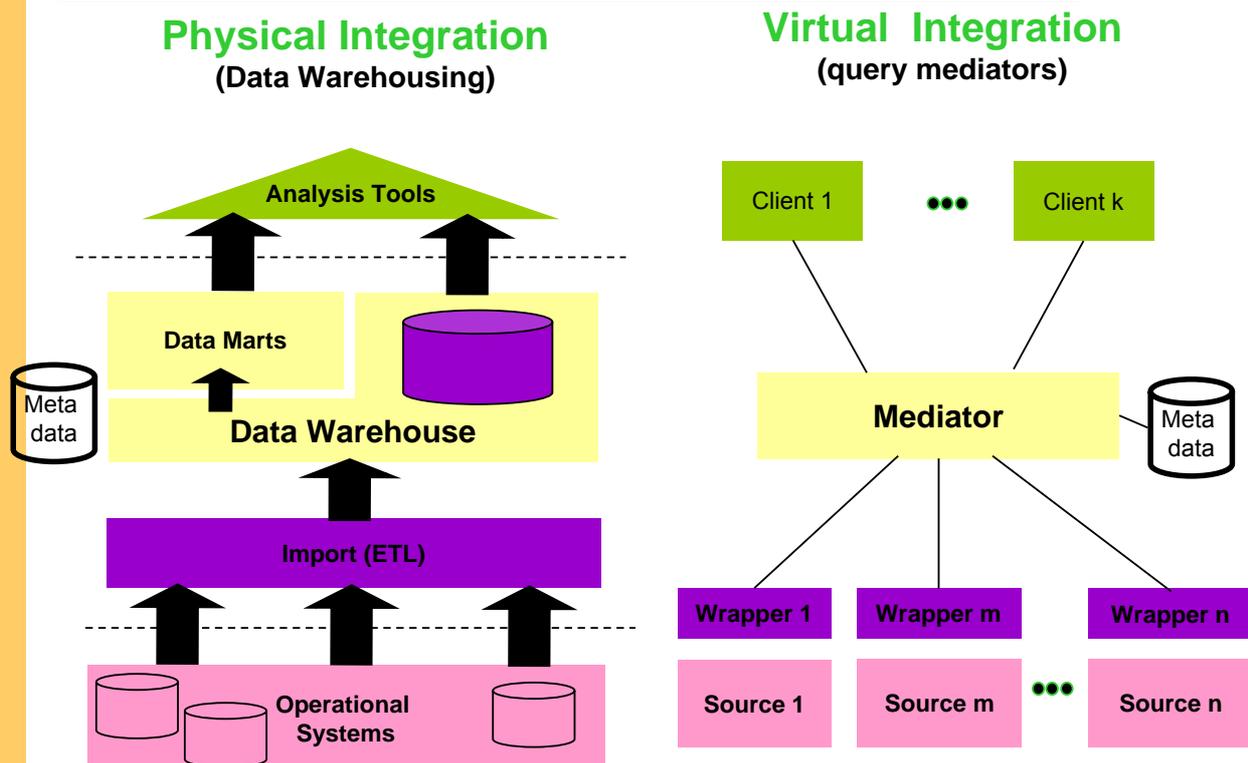
- Anatomies
- Cell Types
- Sequence Attributes
- Temporal Attributes
- Phenotypes
- Diseases
- ....

<http://obo.sourceforge.net/main.html>

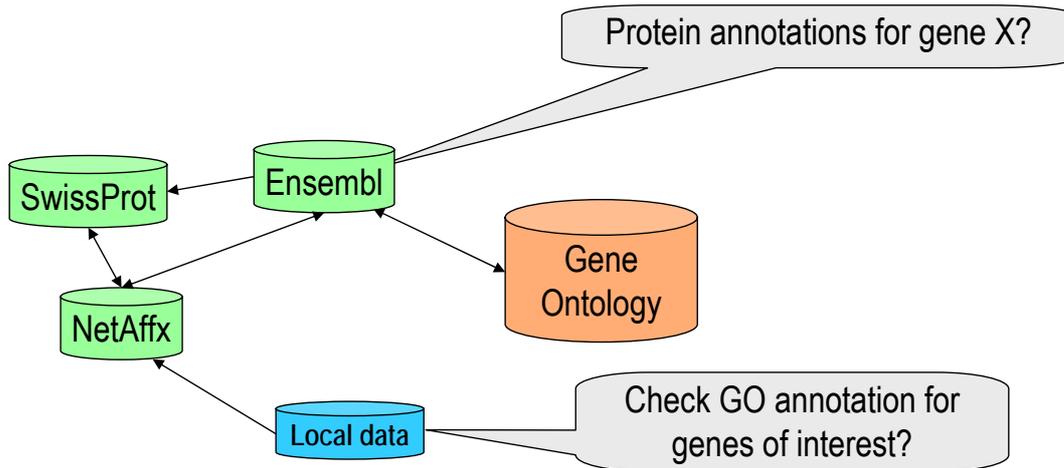
# Agenda

- Kinds of data to be integrated
- General data integration alternatives
  - Physical vs. virtual integration
  - P2P-like / Peer Data Management Systems (PDMS)
  - Scientific workflows
- Warehouse approaches
- Virtual and mapping-based data integration
- Matching large life science ontologies
- Data quality aspects
- Conclusions and further challenges

# Instance integration: Physical vs. virtual



# Peer Data Integration: Typical Scenario

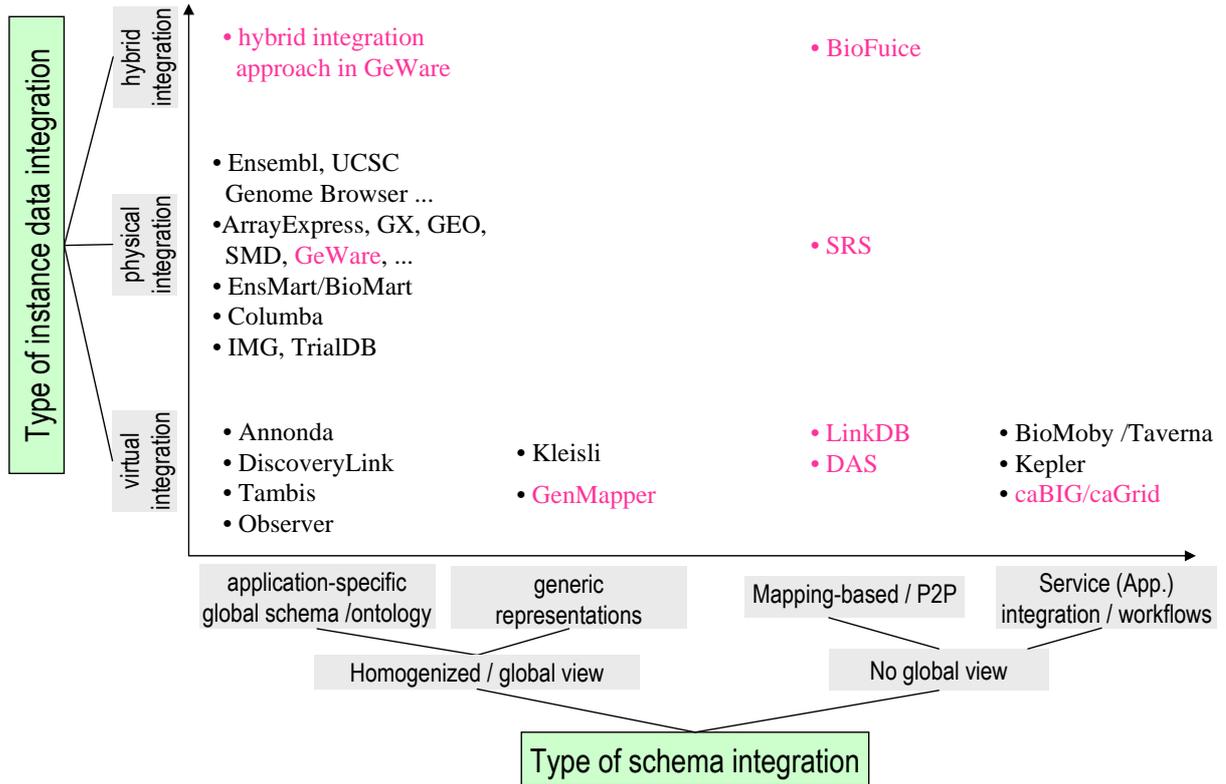


- Bidirectional mappings between data sources instead of global schema
- Queries refer to single source and are propagated to relevant peers
- Adding new sources becomes simpler
  - Support for local data sources (e.g. private gene list)

# Data integration: Physical vs. virtual

	Physical (Warehouse)	Virtual	
		Query mediators	Peer Data Mgmt
Schema integration	A priori	A priori	No schema integration
Instance data integration	A priori	At query runtime	At query runtime
Achievable data quality	+	o	o
Analysis of large data volumes	+	-	-
(HW) resource requirements	-	o	o
Data freshness	o	+	+
Source autonomy	o	+	+
Scalability to many sources	-	-	o

# Classification of data integration approaches



# Application-specific vs. generic representation

## Application-specific global schema

Protein			
Accession	Name	Organism	...
ENSP00000226317	Cytokine B6 precursor	Homo Sapiens	
ENSP00000306512	Interleukin-8 precursor	Homo Sapiens	
...			

## Generic representation using EAV

Metadata

Instance data

Entity	
Entity_ID	Name
1	Protein
2	ProteinFunctionRel
3	Function

Attribute		
Attribute_ID	Entity_ID	Name
1	1	Accession
2	1	Name
3	1	Organism
4	...	...

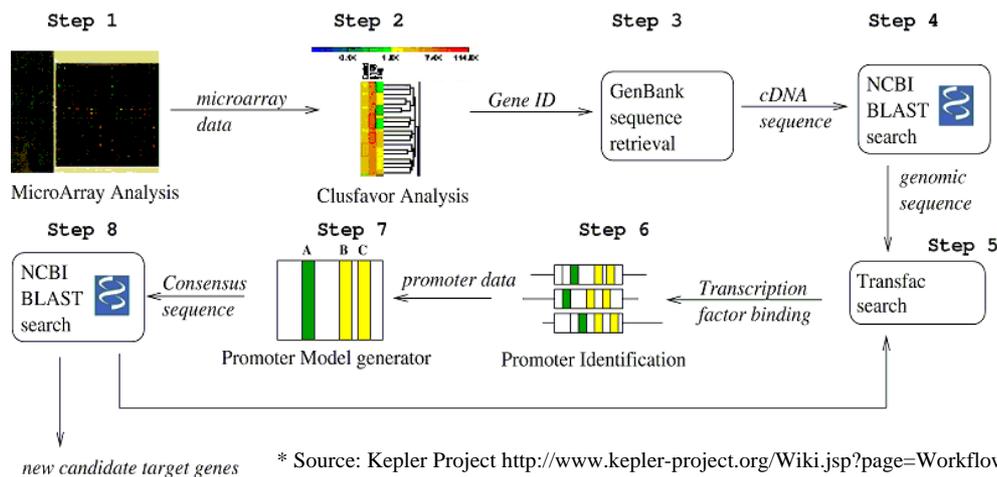
Attribute Value		
Tupel_ID	Attribute_ID	Value
1	1	ENSP00000226317
1	2	Cytokine B6 precursor
1	3	Homo Sapiens
2	1	ENSP00000306512
2	2	...

## Generic representation

Flexible and extensible, but hard to query

# Scientific Workflows

- Integrate data sources at the application (analysis) level
  - Complementary to data-focussed integration approaches
  - Reuse of existing applications, services, and (sub-) workflows
  - Issues: semantically rich service registration, service composition (matching), manipulation of result data, monitoring and debugging workflow execution, ...
- Example: Promoter Identification Workflow\*



\* Source: Kepler Project <http://www.kepler-project.org/Wiki.jsp?page=WorkflowExamples>

# Agenda

- Kinds of data to be integrated
- General data integration alternatives
- Warehouse approaches
  - The GeWare platform for microarray data management
    - Architecture; preprocessing and analysis workflows
    - Integrating data from clinical studies
    - Generic annotation management
  - Hybrid integration for expression + annotation analysis
- Virtual and mapping-based data integration
- Matching large life science ontologies
- Data quality aspects
- Conclusions and further challenges

# The GeWare system\*

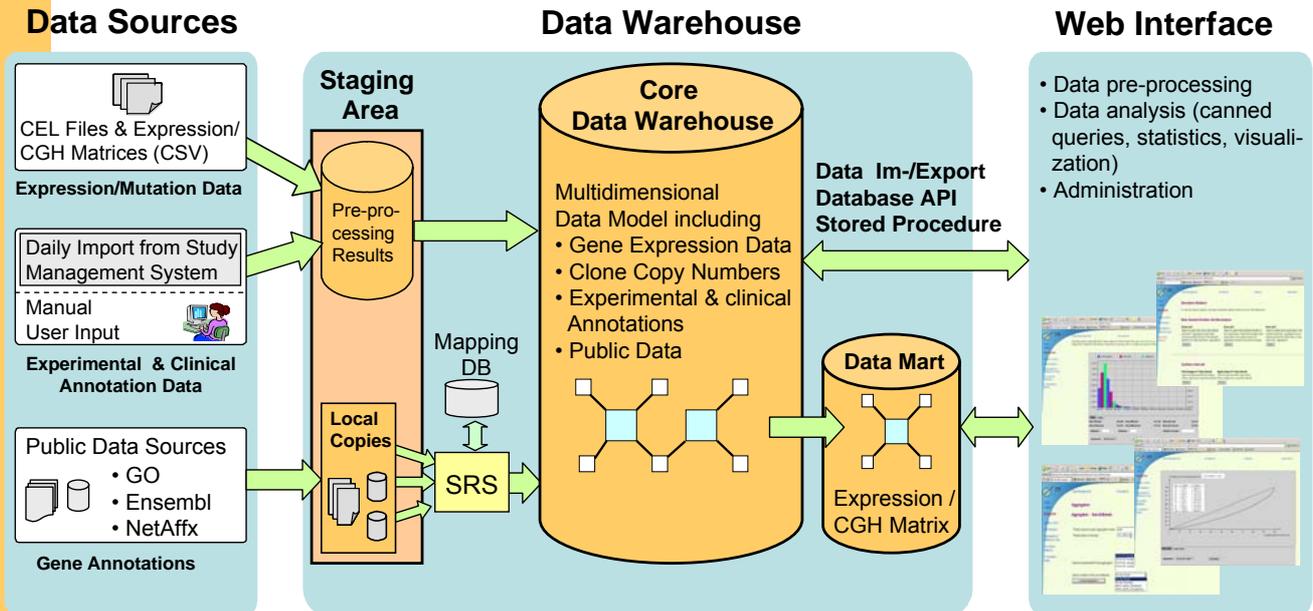
- Many platforms for microarray data management: ArrayExpress (EBI), Gene Expression Omnibus (NCBI), Stanford Microarray Database, ...
- GeWare – Genetic Data Warehouse (U Leipzig)
  - Under development since 2003
- Central data management and analysis platform
  - Data of chip-based experiments (i.e. expression microarrays & Matrix-CGH arrays)
  - Uniform and autonomous specification of experiment annotations
  - Import of clinical data
  - Integration of gene annotations from public sources
  - Various methods for pre-processing, analysis and visualization
  - Coupling with existing tools for powerful and flexible analysis, e.g. R packages, BioConductor

\*Rahm, E; Kirsten, T; Lange, J: *The GeWare data warehouse platform for the analysis molecular-biological and clinical data.* Journal of Integrative Bioinformatics, 4(1):47, 2007

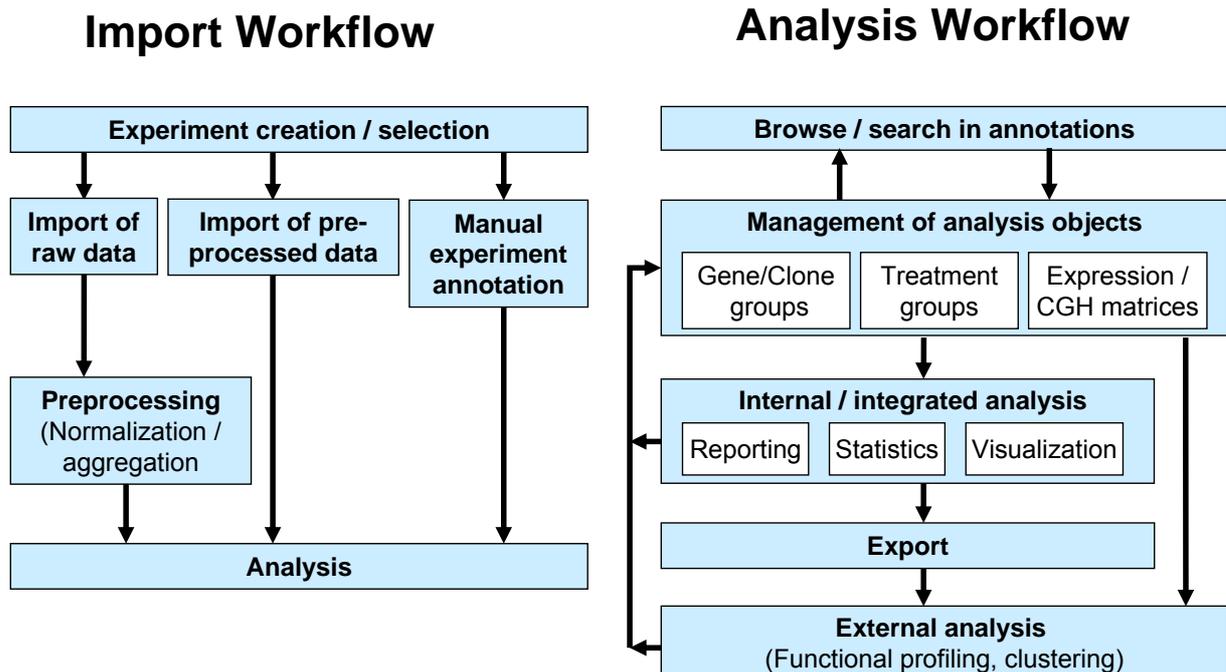
# GeWare Applications

- Two collaborative cancer research studies
  - Molecular Mechanism in Malignant Lymphoma (MMML)  
<http://www.lymphome.de/Projekte/MMML>
  - German Glioma Network: <http://www.gliomnetzwerk.de/>
  - Data from several national clinical, pathological and molecular-genetics centers
  - Experimental and clinical data for hundreds of patients
- Local research groups at the Univ. Leipzig, e.g.
  - Expression analysis of different types of human thyroid nodules
  - Expression analysis of physiological properties of mice
  - Analysis of factors influencing the specific binding of sequences on microarrays

# System architecture

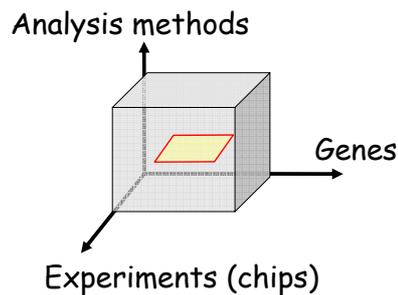


# GeWare – System workflows

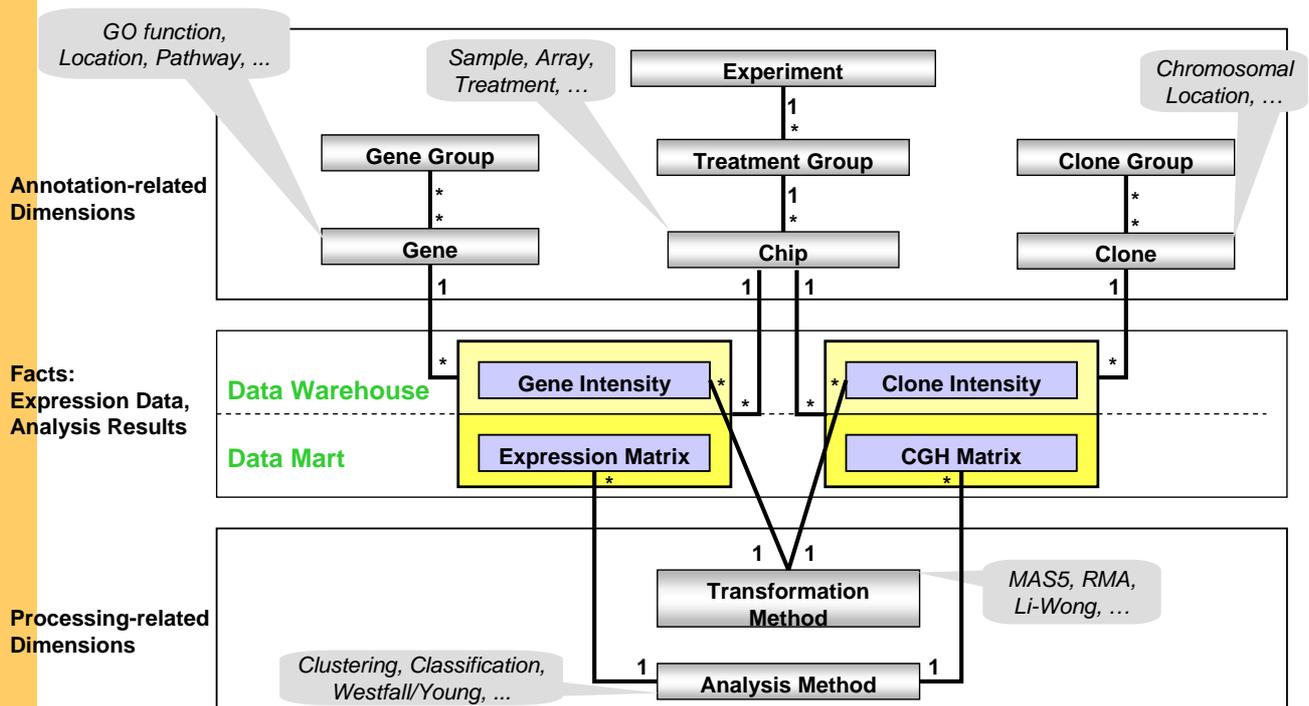


# Multidimensional Data Management

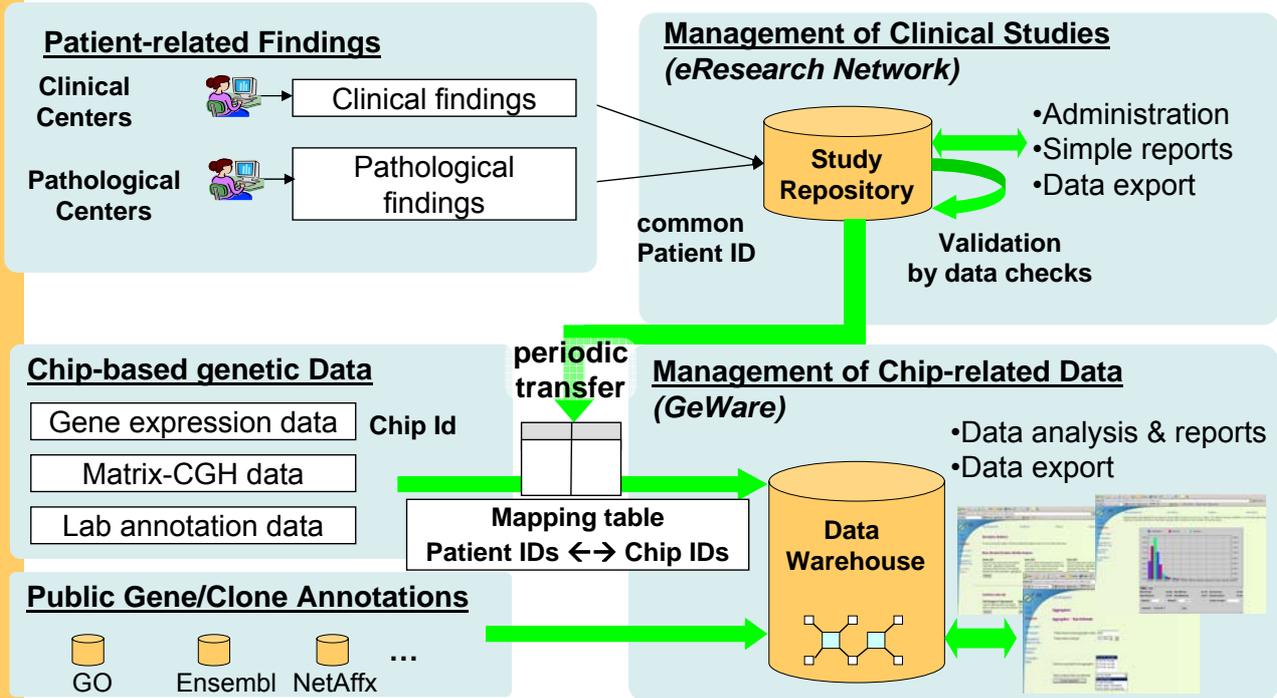
- Fact tables: expression values for different chip types and many chips
  - Scalability and extensibility
- Dimensions (chips/patients, genes, analysis methods)
- Multidimensional analysis
  - Easy selection, aggregation and comparison of values
- Basis to support more advanced analysis methods
  - Focused selection and creation of matrices



# GeWare – Data Warehouse Model



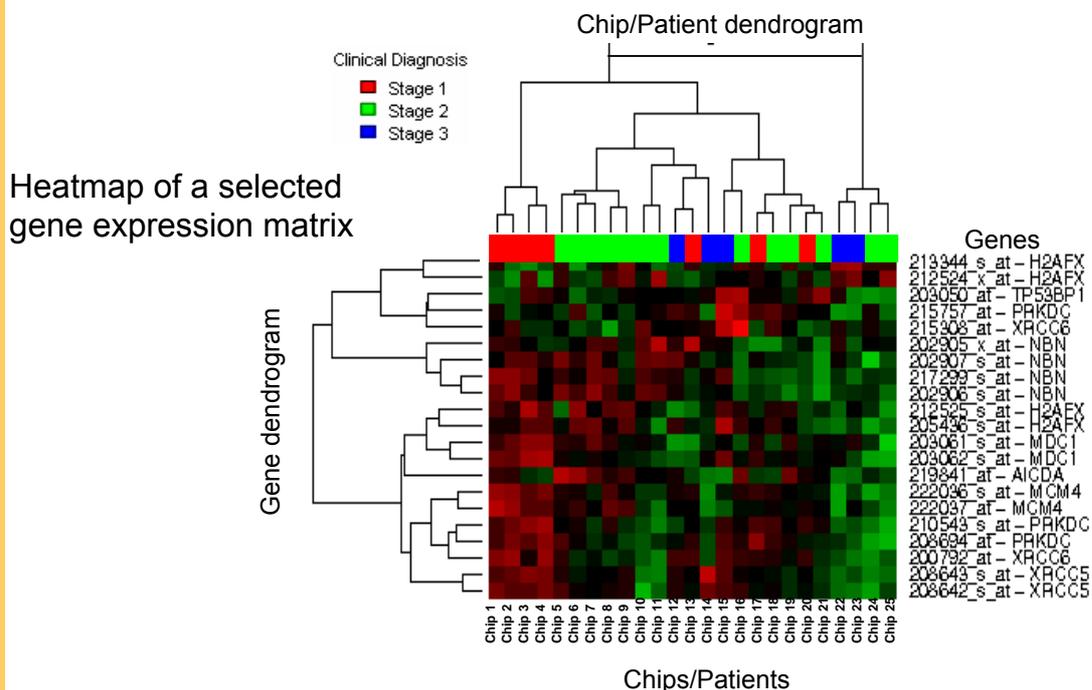
# Clinical data: integration architecture\*



\*Kirsten, T; Lange, J; Rahm, E : *An integrated platform for analyzing molecular-biological data within clinical studies.* Information Integration in Healthcare Application, LNCS 4254, 2006

# Analysis example

- Visualizations of expression values using clinical data



# Annotation management

- Generic approach to specify structure and vocabulary for experimental, clinical and genetic annotations
- Consistent metadata instead of freetext or undocumented abbreviations and naming
- Manual specification of experimental annotations
  - describing the experimental set-up and procedure: sample modifications, hybridization process, utilized devices, ...
- Automatic import of clinical annotations and genetic annotations
- **Annotation templates:**
  - collections of hierarchically structured annotation categories
  - permissible annotation values can be restricted to controlled vocabularies
  - MIAME compliant templates
- Controlled **vocabularies:** locally developed or external (e.g. NCBI Taxonomy)

# Experiment annotation: implementation (1)

- Template example
  - Easy specification and adaptation
  - Association of available vocabularies

**Category Definitions**  
Page: *Hybridization Conditions*

[back to Page Definitions](#)

Please note: Select boxes, check boxes and radios have to possess a vocabulary.  
All other types don't have a predefined vocabulary.

Name	Parent	Position	Type	Vocabulary	Mandatory	MagE-ML
			heading 1		<input type="radio"/> yes <input checked="" type="radio"/> no	
Buffer		1	single choice (select box)	Hybridization Buffers	<input checked="" type="radio"/> yes <input type="radio"/> no	BioAssay-Package > Hybridization
Pre-Hybridization v		2	single choice (select box)	Decision y/n	<input type="radio"/> yes <input checked="" type="radio"/> no	BioAssay-Package > Hybridization
Competitors		3	multiple choice (check box)	Hybridization Competitors	<input checked="" type="radio"/> yes <input type="radio"/> no	BioAssay-Package > Hybridization
Hybridization Devi		4	single choice (select box)	Hybridization Devices	<input type="radio"/> yes <input checked="" type="radio"/> no	BioAssay-Package > Hybridization
Hybridization Instri		5	single choice (select box)	Hybridization Instruments	<input type="radio"/> yes <input checked="" type="radio"/> no	BioAssay-Package > Hybridization
Temperature in de		6	input field		<input type="radio"/> yes <input checked="" type="radio"/> no	BioAssay-Package > Hybridization
Buffer Volume in n		7	input field		<input type="radio"/> yes <input checked="" type="radio"/> no	BioAssay-Package > Hybridization
Hybridization Leng		10	input field		<input type="radio"/> yes <input checked="" type="radio"/> no	BioAssay-Package > Hybridization

**Term Definitions**  
Vocabulary: *Hybridization Buffers*

Name	Description	
		New
Ambion Northern Maxim	Northern Maximum	Save Remove
Clontech Express H	Express Hybridization	Save Remove
Genisphere 3 D	Genisphere 3 DNA	Save Remove
Genisphere DNA form	phere 3 DNA formamide	Save Remove

## Experiment annotation: implementation (2)

- Template example
  - Automatically generated web GUI
  - Hierarchically ordered categories

**Chip Annotation: CL2001042127AA**  
Experiment: Battacharjee COID, ChipMethod: Gene Expression, Template: Human Biopsy

Generated page to capture annotation values

**Hybridization Conditions**

Utilization of terms of associated vocabularies

Index page

## Experiment annotation: application

- Search in experiment annotation: Create treatment groups (later reuse in analysis)

**Browse Chip Annotation**  
Template: Human Biopsy

Generate Query

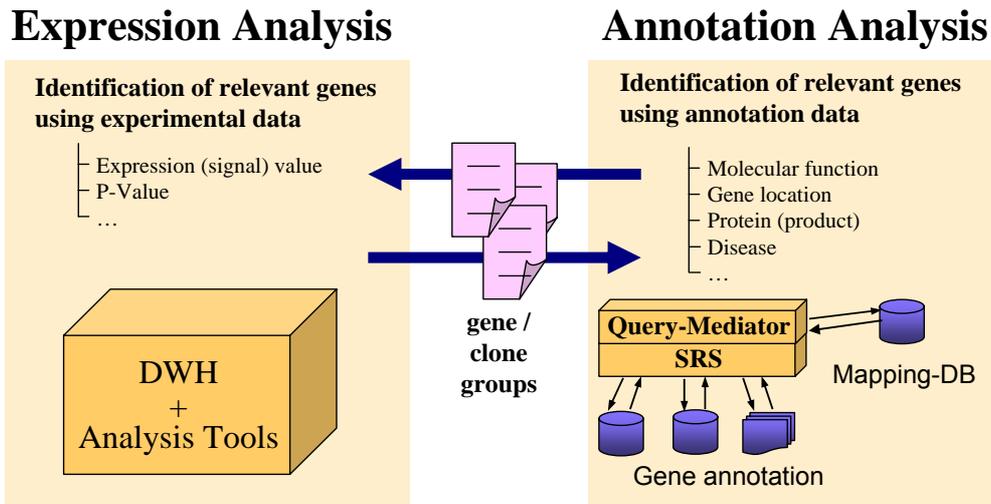
Search for relevant chips by specifying queries

Save result as group

Chip name	Chip type	
CH1999021101AA	HuGeneFI	Browse Annotation
CH1999021103AA	HuGeneFI	Browse Annotation
CH1999021105AA	HuGeneFI	Browse Annotation
CH1999021106AA	HuGeneFI	Browse Annotation

Save as Group [ ] OK

# Hybrid integration of data sources\*



\*Kirsten, T; Rahm, E: *Hybrid integration of molecular-biological annotation data.*  
Proc. 2<sup>nd</sup> Intl. Workshop DILS, July 2005

## Agenda

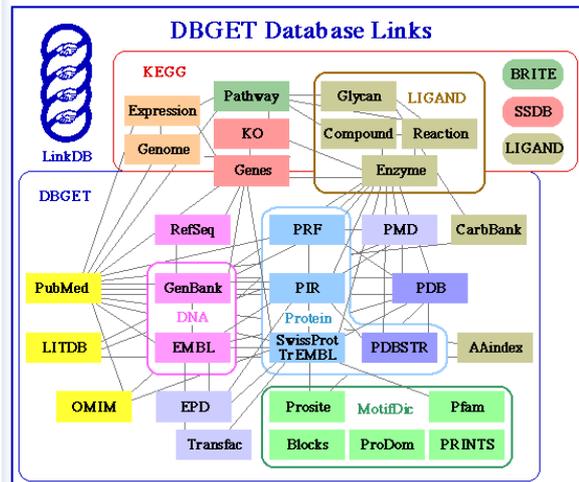
- Kinds of data to be integrated
- General data integration alternatives
- Warehouse approaches
- Virtual and mapping-based data integration
  - Web-link integration: DBGet/LinkDB
  - GenMapper
  - Distributed Annotation System (DAS)
  - Sequence Retrieval System (SRS)
  - BioFuice
- Matching large life science ontologies
- Data quality aspects
- Conclusions and further challenges

# Integration based on available web-links

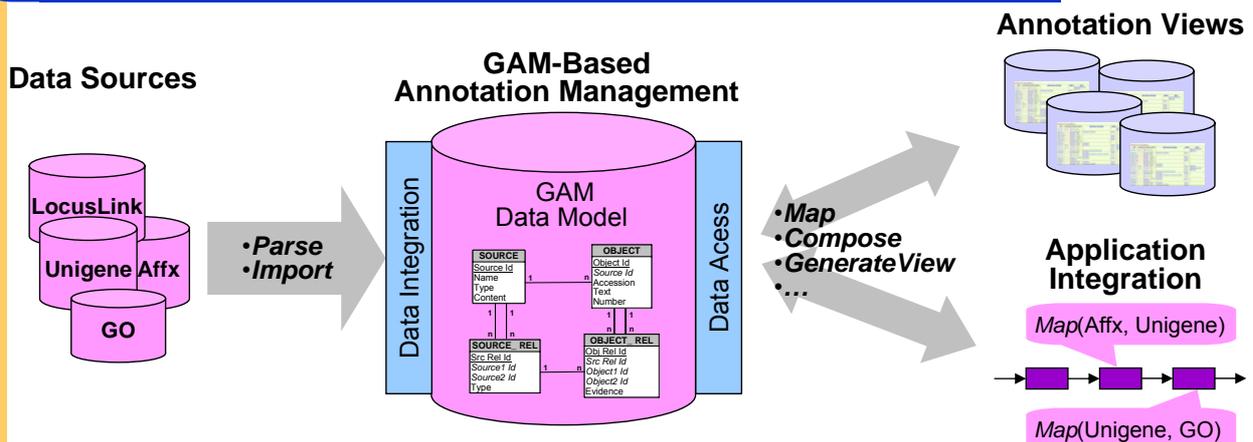
- Web-Link = URL of a source + ID of the object of interest
- Simple integration approach
  - Little integration effort
  - Scalable
  - Navigational analysis: only one object at a time
- DBGET + LinkDB:

- Collection of web-links between many sources
- Management of source specific sets of object ID and their connecting mappings
- No explicit mapping types

[www.genome.jp/dbget/](http://www.genome.jp/dbget/)



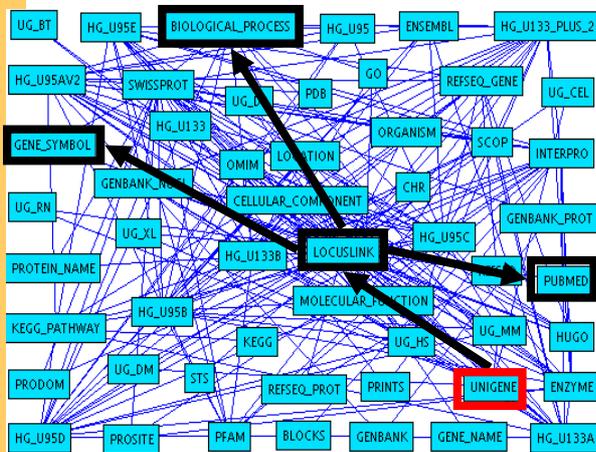
# GenMapper\*



- *Generic data model, GAM*, to uniformly represent annotation data
  - Flexible w.r.t. heterogeneity, evolution and integration
- Exploits *existing mappings* between objects/sources
  - Valuable knowledge, available in almost every source, scalable
- *High-level operations* to support data integration and data access
- *Tailored annotation views* for specific analysis needs

\*Do, H.H.; Rahm, E.: *Flexible integration of molecular-biological annotation data: The GenMapper approach*. Proc. 9th EDBT Conf., 2004

# GenMapper: Usage scenario

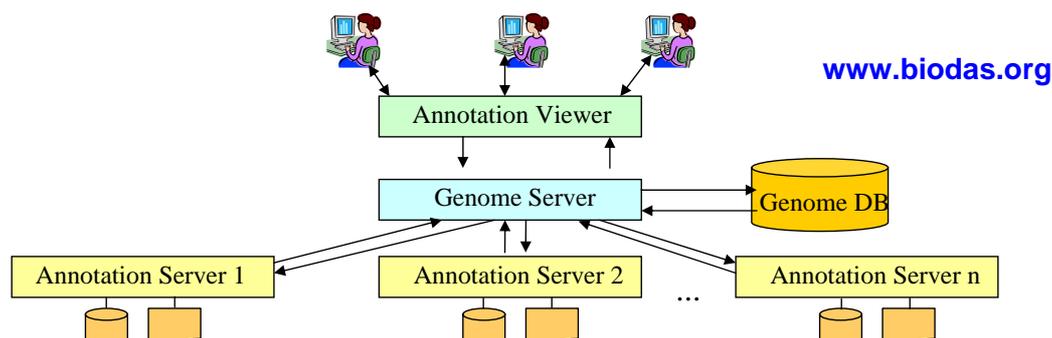


Annotation view

UG_HS	GENE_SYMBOL	BIOLOGICAL_PROCESS	PUBMED
Hs.100002	b1p, Dncl2a, DNLC2A, B1TH, HSPC162, MGC15113	GO:0007018, GO:0007632	
Hs.100007	RFK2, FLJ14226	GO:0006355	
Hs.100009	CDK3	GO:0000074, GO:0006468, GO:0007067	1639063
Hs.100057	STK35, CLIK1	GO:0006468	
Hs.100058	DPYSL4, CRMP3, DRP-4, ULIP4	GO:0007399	8973361, 9652388
Hs.100071	PGLS, 6PGL	GO:0005975, GO:0006098	10518023
Hs.100072	GJA12, Cx47, CX46.6, PMLDAR	GO:0007154	
Hs.100194	ALOX5AP, FLAP	GO:0006954, GO:0019370	1673682, 10036194

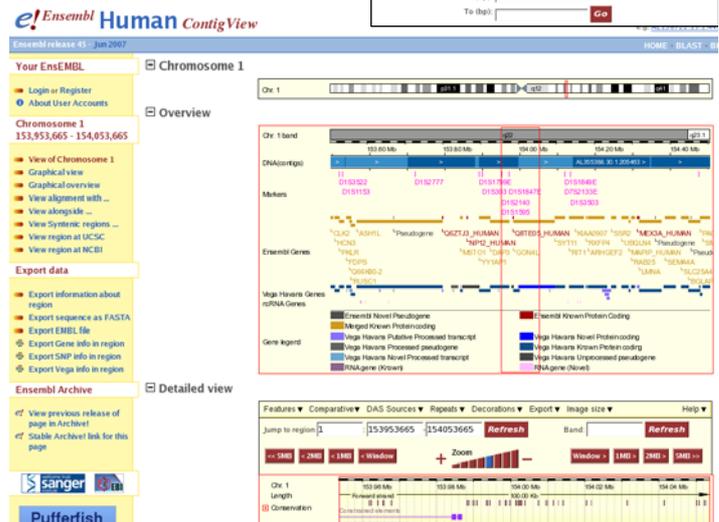
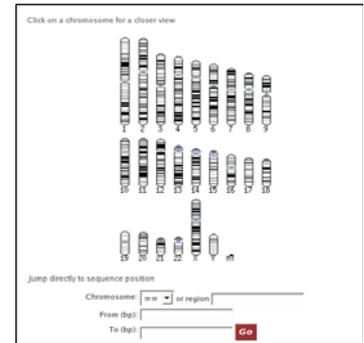
# Distributed Annotation System (DAS)

- Integration of distributed data sources with central genome server
  - Genome server: Primary source containing reference genome sequence
  - Annotation server: Wrapped source of a research group / organization
- Annotations are mapped to a reference genome sequence
  - Only sequence coordinates for each object are necessary (i.e., chr, start, stop, strand)
  - Simple and scalable approach
  - Recalculation of all annotations when the reference sequence has changed



# DAS: Query processing

- Query formulation
  - Select organism and chromosome from reference genome
  - Position-based (range) queries for associated objects
- Query processing
  - Send range query to genome DB and relevant annotation servers
  - Merge retrieved results
- Query result can be viewed on the genome at different detail levels with associated annotations, i.e., objects of different types

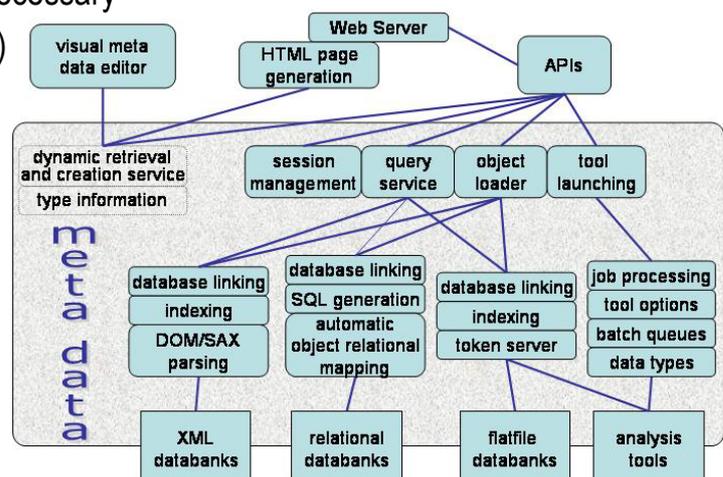


E. Rahm et al.: Data Integration in Bioinformatics and Life Sciences

# Sequence Retrieval System (SRS)

- Originally developed for accessing sequence data at EMBL
  - Commercial version by BioWisdom (before: Lion Bioscience)
- Data integration primarily for file data sources, but extended for database access and analysis tools
  - Mapping-based integration, no global schema
  - Local installation of sources necessary
  - Indexing (queryable attributes) of file-based sources by a proprietary script language
  - Definition of hub-tables (and queryable attributes) in relational sources
- Large wrapper library available for public sources

Source: Lion BioScience



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# SRS: Query formulation and processing

- Query formulation
  - Source selection
  - Filter specification for queryable attributes
- Query types
  - Keyword search
  - Range search for numeric and date attributes
  - Regular expressions
- Automatic translation to SQL queries for relational sources
- Merge of result sets
  - Intersection
  - Union

# SRS: Query formulation and processing cont.

- Explorative analysis
  - Traverse selected objects to objects of another data source
- Automatically generated paths between sources
  - Shortest paths (Dijkstra)
  - No consideration of path / mapping semantics
  - No join, only source graph traversal
- Result
  - Set of associated objects
  - No explicit mapping data (object correspondences) retrieved

## BioFuice\*: Design goals

- Utilization of instance-level cross-references (often manually curated, high quality data): *instance-level mappings* between sources
- Navigational access to many sources
- Support for queries and ad-hoc analysis workflows
- Often no full transparency necessary: users want to know from which sources data comes (data lineage / provenance)
- Support for integrating local (non-public) data
- Support for object matching and fusion (data quality)
- Creation of new instance mappings

-> Mapping-based data integration

\*Kirsten, T; Rahm, E: *BioFuice: Mapping-based data integration in bioinformatics*. Proc. 3<sup>rd</sup> DILS, 2006

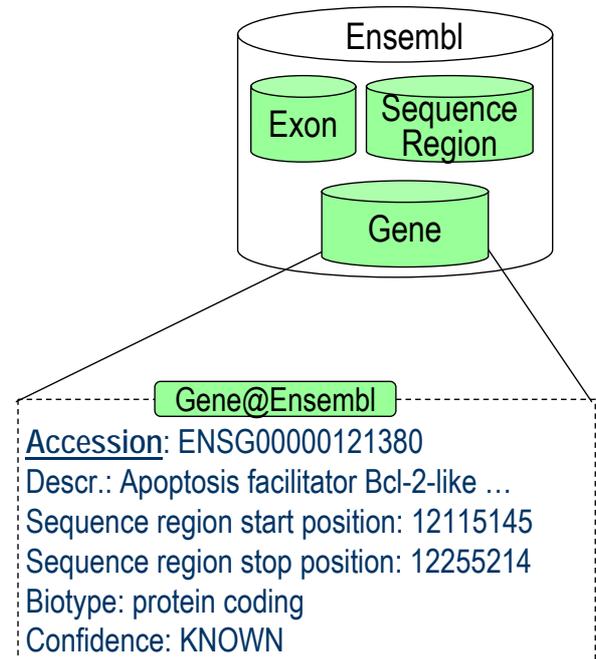
## BioFuice (2)

- **BioFuice**: **B**ioinformatics information **f**usion **u**tilizing **i**nstance **c**orrespondences and **p**eer mappings
- Basis: iFuice approach\*
  - Generic way to information fusion
  - **High-level operators**
- **P2P**-like infrastructure
  - Mappings between autonomous data sources (peers), e.g. sets of instance correspondences
  - Simple addition of new sources where they fit best
- Mapping mediator
  - Mapping management and operator execution
  - Downloadable sources are materialized for better performance (hybrid integration)
  - Utilization of application specific **semantic** domain model

\* Rahm, E., et al.: *iFuice - Information Fusion utilizing Instance Correspondences and Peer Mappings*. Proc. 8<sup>th</sup> WebDB, Baltimore, June 2005

# BioFuice: Data sources

- **Physical data source (PDS)**
  - Public, private and local data (gene list, ...), ontologies
  - Splitted into logical data sources
- **Logical data source (LDS)**
  - Refers to one object type and a physical data source, e.g. Gene@Ensembl
  - Contains object instances
- **Object instances**
  - Set of relevant attributes
  - One **id** attribute

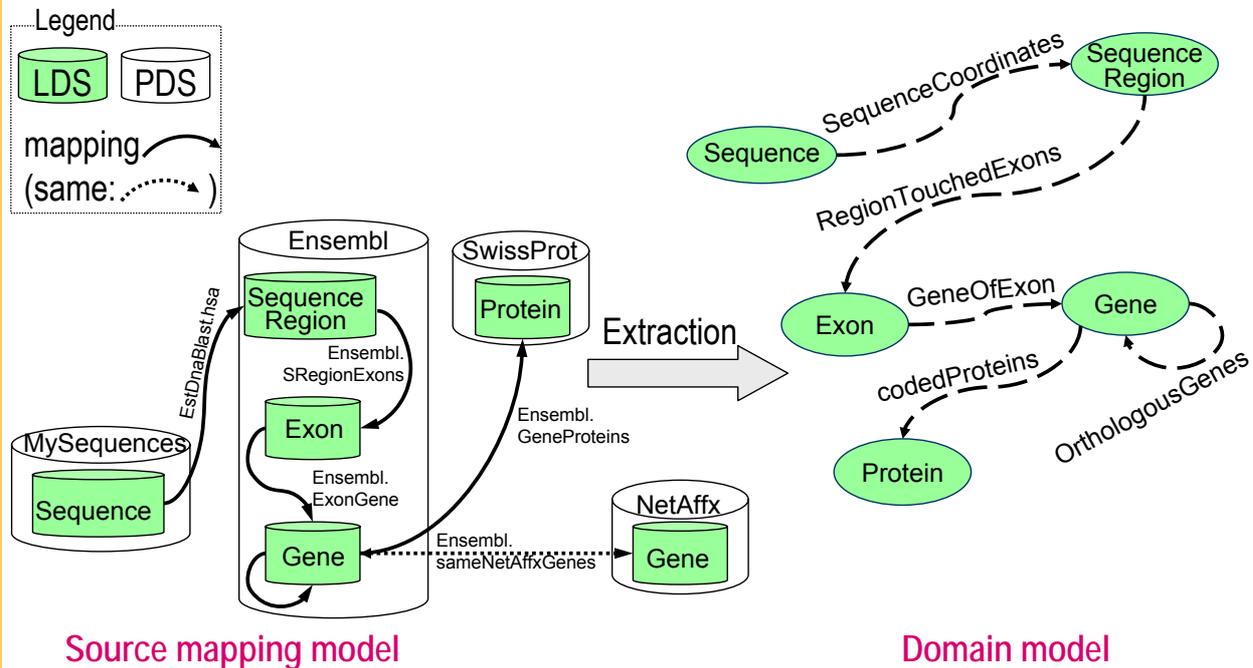


# BioFuice Mappings

- Directed relationships between LDS
- Mappings have a semantic **mapping type**
  - E.g. OrthologousGenes
- Different kinds of mappings
  - **Same mappings** vs. **Association mappings**
    - Same: equality relationship
  - **ID mappings** vs. **computed mappings** (e.g. query mappings)
  - Materialized mappings (mapping tables) vs. dynamic generation (on the fly)

## BioFuice: metadata models

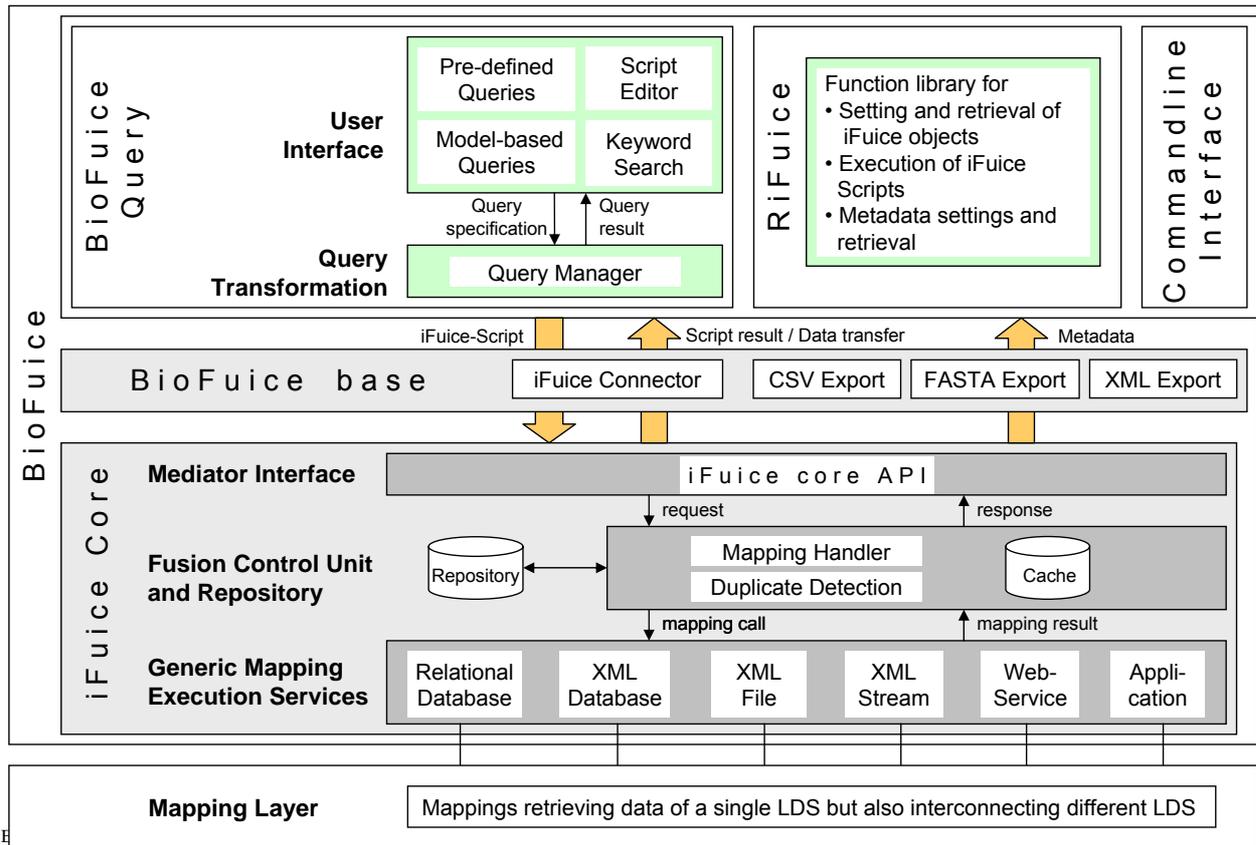
- Used by mediator for mapping/operator execution
- Domain model** indicates available object types and relationships



## BioFuice Operators

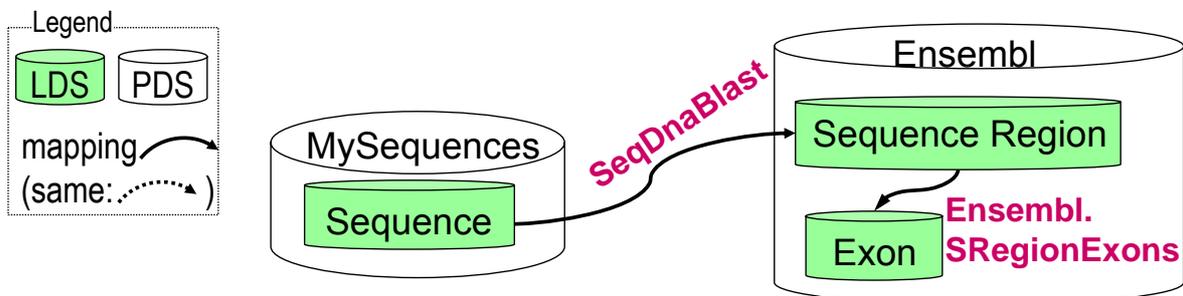
- Query capabilities + scripting support
  - Set oriented operators**
    - Input: Set of objects/mappings + parameters / query conditions
    - Output: Set of resulting objects
- ⇒ Combination of operators within scripts for workflow-like execution
- Selected operators:
    - Single source: [queryInstances](#), [searchInstances](#), ...
    - Navigation: [traverse](#), [map](#), [compose](#), ...
    - Navigation + aggregation: [aggregate](#), [aggregateTraverse](#), ...
    - Generic: [diff](#), [union](#), [intersect](#), ...

# BioFuice architecture



# BioFuice: Script example

- Scenario
  - Given: Set of sequences in local source MySequences
  - Wanted: Three classes: unaligned s., non-coding s., protein coding sequences



```

$alignedSeqMR := map( MySequences, { SeqDnaBlast } );
$unalignedSeqOI := diff ( MySequences, domain ( $alignedSeqMR ));
$codingSeqMR := compose( $alignedSeqMR, { Ensembl.SRegionExons } );
$protCodingSeqOI := domain ( $codingSeqMR );
$nonCodingSeqOI := diff ( domain ( $alignedSeqMR ), $protCodingSeqOI );
    
```

# BioFuice Query Processing

Current connection: localhost:C:\JavaPrograms\ifuice\ifuice-test.ini  
Done.

E. Rahm et al.: Data Integration in Bioinformatics and Life Sciences

EDBT summer school 2007

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## iFuice application: citation analysis\*

- Citation analysis important for evaluating scientific impact of publications venues, researchers, universities etc.
  - What are the most cited papers of journal X or conference Y?
  - What is the H-index of author Z ?
  - Frequent changes: new publications & new citations
- Idea: Combine publication lists, e.g. from DBLP or Pubmed, with citation counts, e.g from Google Scholar, Citeseer or Scopus
- Warehousing approach, virtual (on the fly) or hybrid integration
- Fast approximate results by **Online Citation Service (OCS)\*\***
  - <http://labs.dbs.uni-leipzig.de/ocs>

\* Rahm, E, Thor, A.: *Citation analysis of database publications*. ACM Sigmod Record, 2005

\*\* Thor, A., Aumueller, D., Rahm, E.: *Data integration support for Mashups*. Proc. IIWeb 2007

# Sample OCS result

## OCS result for venue Bioinformatics 2004

- Found 358 GS publications for 336 DBLP publications.
- No GS publications found for 225 DBLP publications.
- Overall: 561 DBLP publications having 7448 citations.
- Average: 13,3 citations per publication.
- H-Index: 41
- Match configuration: 80% title similarity, max. 0 year(s) difference, 50% author similarity.

Title	Year	Authors
80%	+/- two years	50%
85%	+/- one year	60%
90%	Equal year	70%
95%		80%
100%		90%
		100%

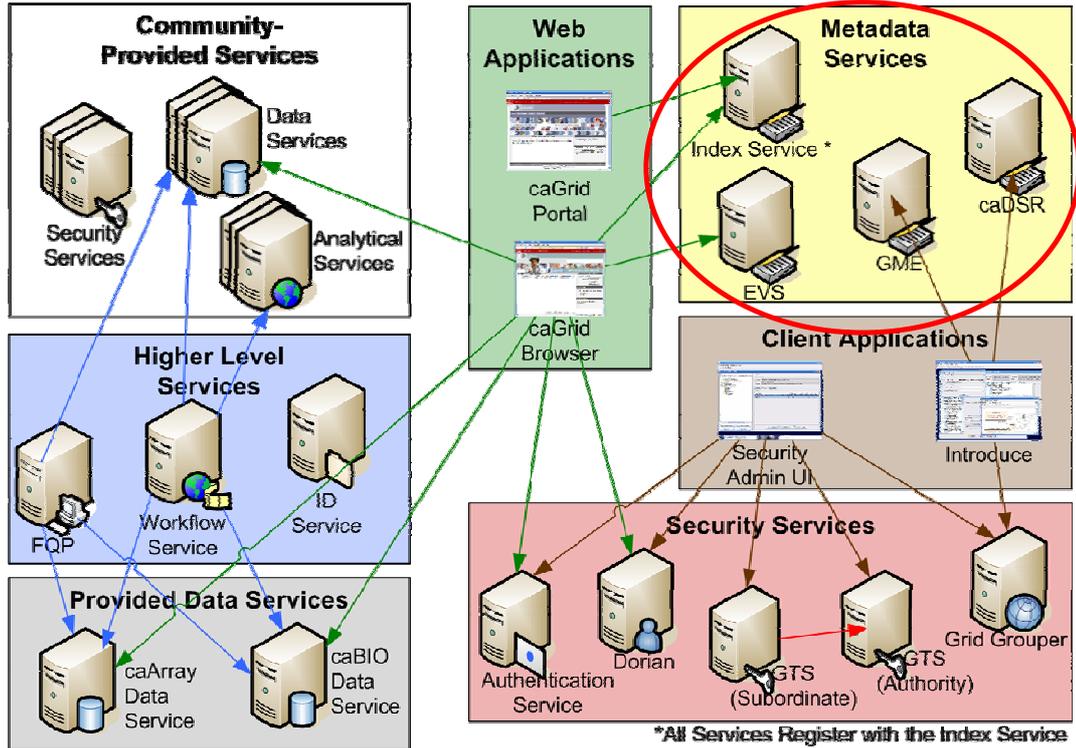
	Title	Authors	Venue	Year	Citation ▼
+	FatiGO: a web tool for finding significant associations of Gene Ontology terms with groups of genes.	Fátima Al-Shahrour, Ramón Díaz-Uriarte, Joaquín Dopazo	Bioinformatics	2004	289
-	Taverna: a tool for the composition and enactment of bioinformatics workflows. T Oinn, M Addis, J Ferris, D Marvin, M Senger, M : <i>Taverna: a 215 tool for the composition and enactment of bioinformatics workflows</i> (2004) T Oinn, M Addis, J Ferris: <i>other authors</i> (2004). <i>Taverna: a tool for the composition and enactment of bioinformatics workflows</i> T Oinn, M Addis, J Ferris, D Marvin, M Senger, M : , A. Wipat, 2 and P. Li. <i>Taverna: a tool for the composition and enactment of bioinformatics workflows</i>	Thomas M. Oinn, Matthew Addis, Justin Ferris, Darren Marvin, Martin Senger, R. Mark Greenwood, Tim Carver, Kevin Glover, Matthew R. Pocock, Anil Wipat, Peter Li	Bioinformatics	2004	219
+	The Jalview Java alignment editor.	Michele E. Clamp, James A. Cuff, Stephen M. J. Searle, Geoffrey J.	Bioinformatics	2004	212

# caBIG™/caGRID\*

- **ca**ncer **Bi**omedical **I**nformatics **G**rid™ (caBIG™)
  - Virtual network connecting individuals and organizations to enable the sharing of data and tools, creating a World Wide Web of cancer research
  - Overall goal: Speed the delivery of innovative approaches for the prevention and treatment of cancer
- **Objectives**
  - Common, widely distributed infrastructure that permits the cancer research community to focus on innovation
  - Service-based integration of applications and data
  - Shared, harmonized set of terminology, data elements, and data models that facilitate information exchange to overcome syntactic and semantic interoperability
  - Collection of interoperable applications developed to common standards
  - Raw published cancer research data is available for mining and integration

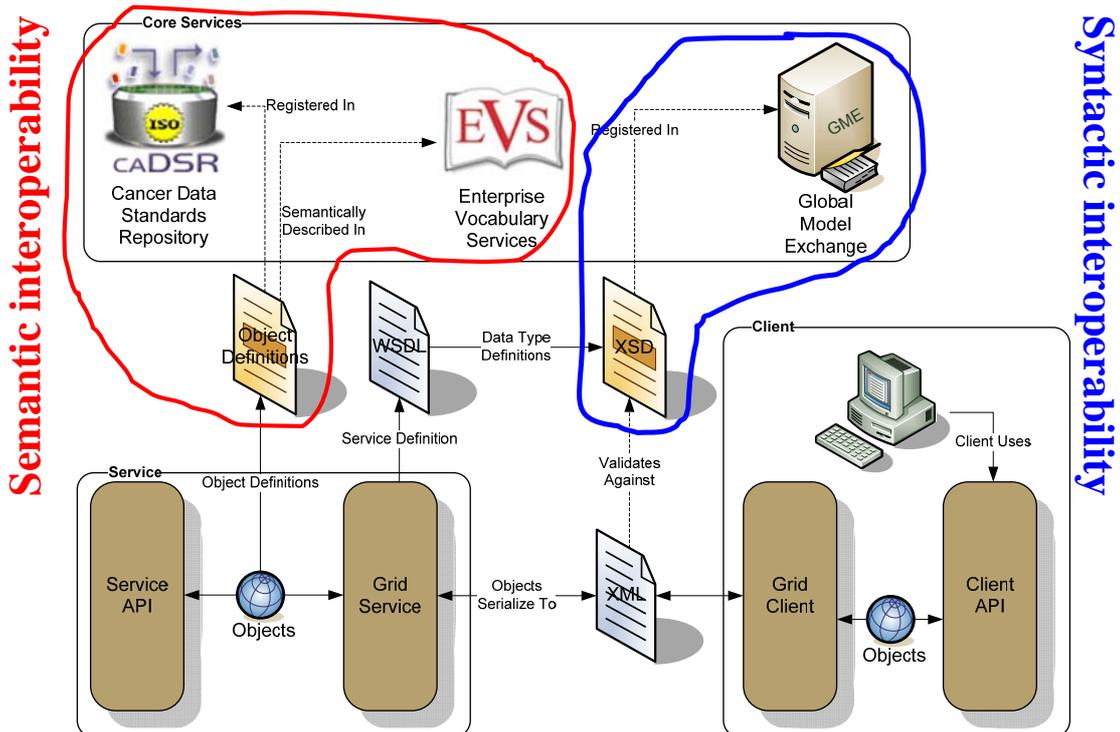
\*Joel H. Saltz, et al.: *caGrid: design and implementation of the core architecture of the cancer biomedical informatics grid*. Bioinformatics, Vol. 22, No. 15, 2006, pp. 1910-1916

# Service-based data integration in caGrid



Source: T. Kurc et al.: Panel Discussion, caBIG Annual Meeting 2007

# caBIG/caGRID: Data description infrastructure



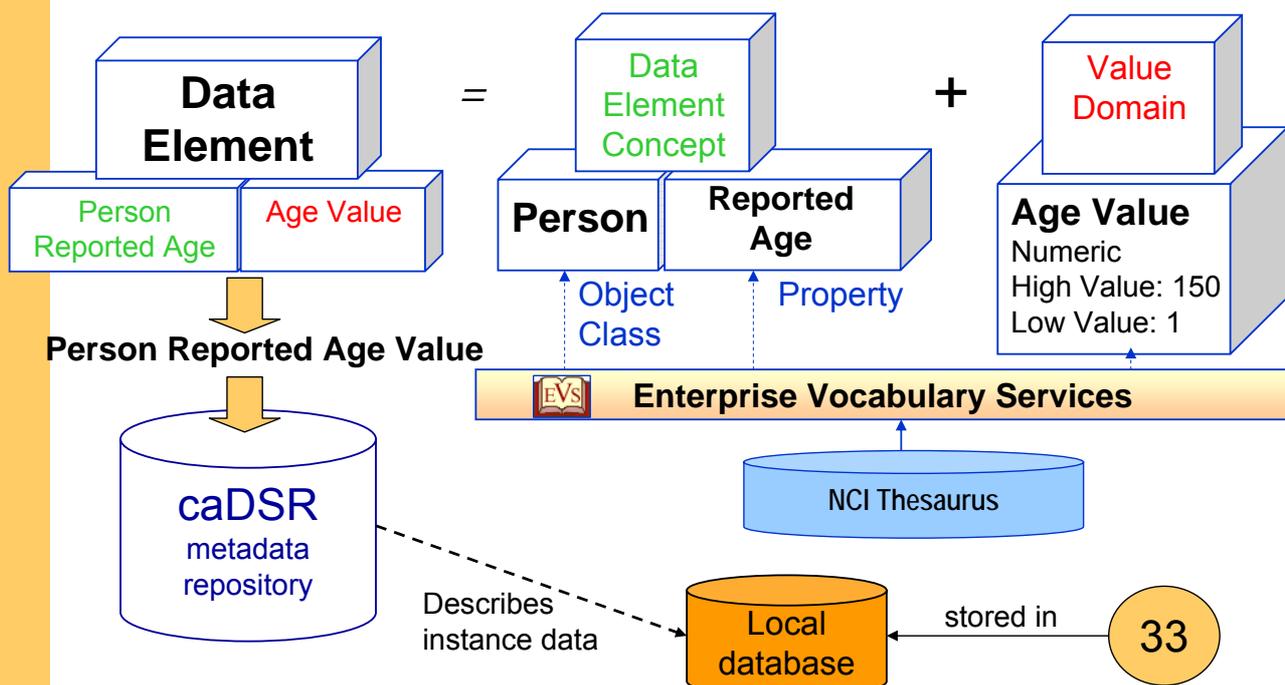
# caBIG/caGRID: Basis Vocabulary -NCI Thesaurus

- About NCI Thesaurus
  - Reference terminology for NCI
  - About 54000 concepts in 20 hierarchies
  - Broad coverage of cancer domain
    - Findings and Disorders
    - Anatomy
    - Drugs, Chemicals
    - Administrative Concepts
    - Conceptual Entities/Data Types
- Advantages
  - Uniform conceptualization in a domain
  - Standardization, interoperability, classification
  - Enable reuse of data and information
- Usage in caBIG/caGrid
  - Annotation of medical data (images, ...)
  - Service Discovery in grids
  - Building of Common Data Elements (CDE) for exchange of medical data

## NCI\_Thesaurus Taxonomy

- [-] Abnormal Cell
- [-] Activity
- [-] Anatomic Structure, System, or Substance
  - [-] Body Fluid or Substance
  - [-] Body Part
  - [-] Body Region
  - [-] Body Cavity
  - [-] Embryologic Structure or System
  - [-] Microanatomic Structure
- [-] Organ
  - [-] Biliary Tract
  - [-] Bladder
  - [-] Bone Marrow
  - [-] Brain
  - [-] Breast
  - [-] Bronchial Tree
  - [-] Diaphragm
  - [-] Duct
  - [-] Epididymis
  - [-] Esophagus
  - [-] Fallopian Tube
  - [-] Gall Bladder
  - [-] Gland
  - [-] Gonad
  - [-] Heart

# caBIG/caGRID: Building common data elements

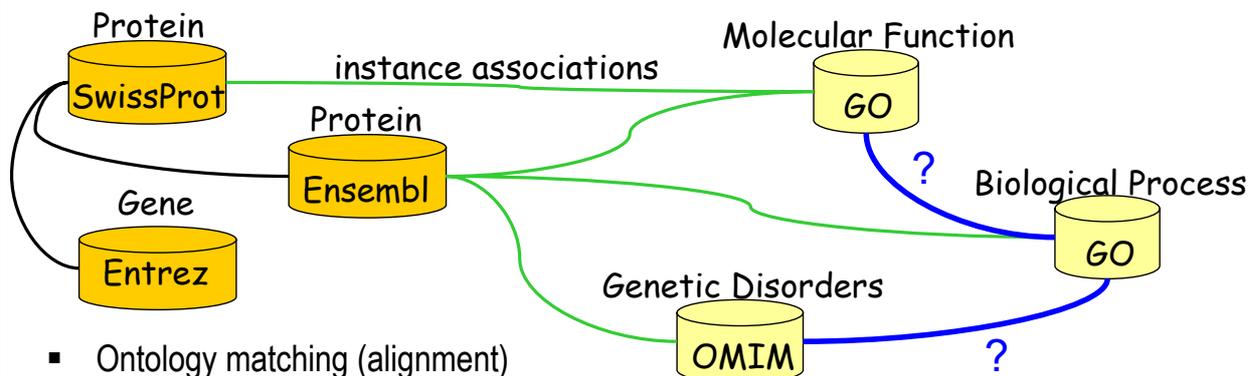


# Agenda

- Kinds of data to be integrated
- General data integration alternatives
- Warehouse approaches
- Virtual and mapping-based data integration
- Matching large life science ontologies
  - Motivation
  - Match approaches and frameworks (Coma++, Prompt, Sambo)
  - Instance-based match approach (DILS07), evaluation results
- Data quality aspects
- Conclusions and further challenges

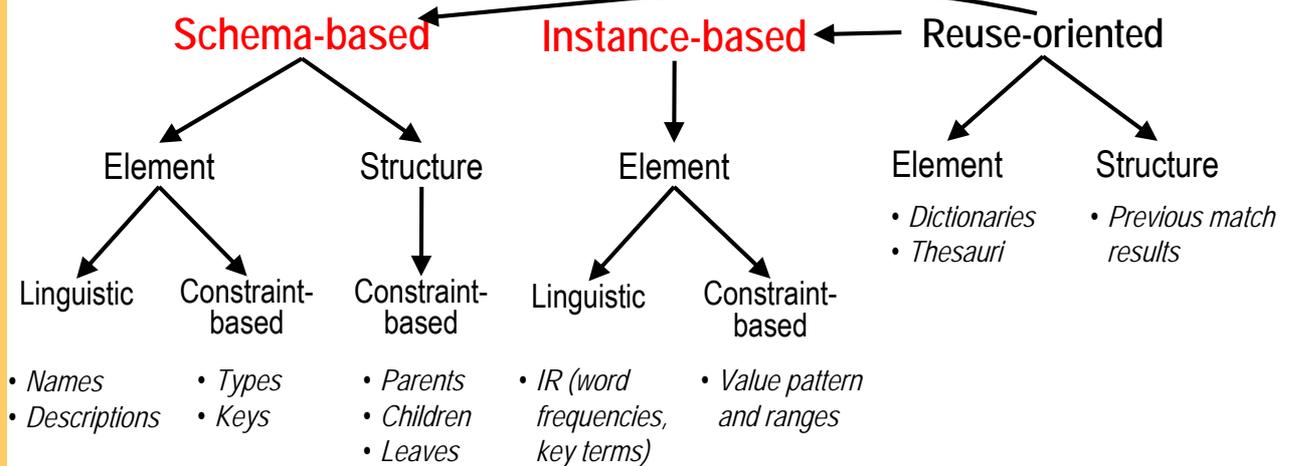
# Motivation

- Increasing number of connected sources and ontologies



- Ontology matching (alignment)
  - Goal: Find semantically related concepts
  - Output: Set of correspondences (ontology mapping)
    - Ideally: + semantic mapping type (equivalence, is-a, part-of, ...)
  - Use:
    - Improved analysis
    - Validation (curation) and recommendation of instance associations
    - Ontology merge or curation, e.g. to reduce overlap between ontologies

# Automatic Match Techniques\*



- Combined Approaches: Hybrid vs. Composite
- Many frameworks / prototypes: COMA++, Prompt, FOAM, Clio, ... but mostly not used in bioinformatics

\*Rahm, E., P.A. Bernstein: *A Survey of Approaches to Automatic Schema Matching*. VLDB Journal 10(4), 2001

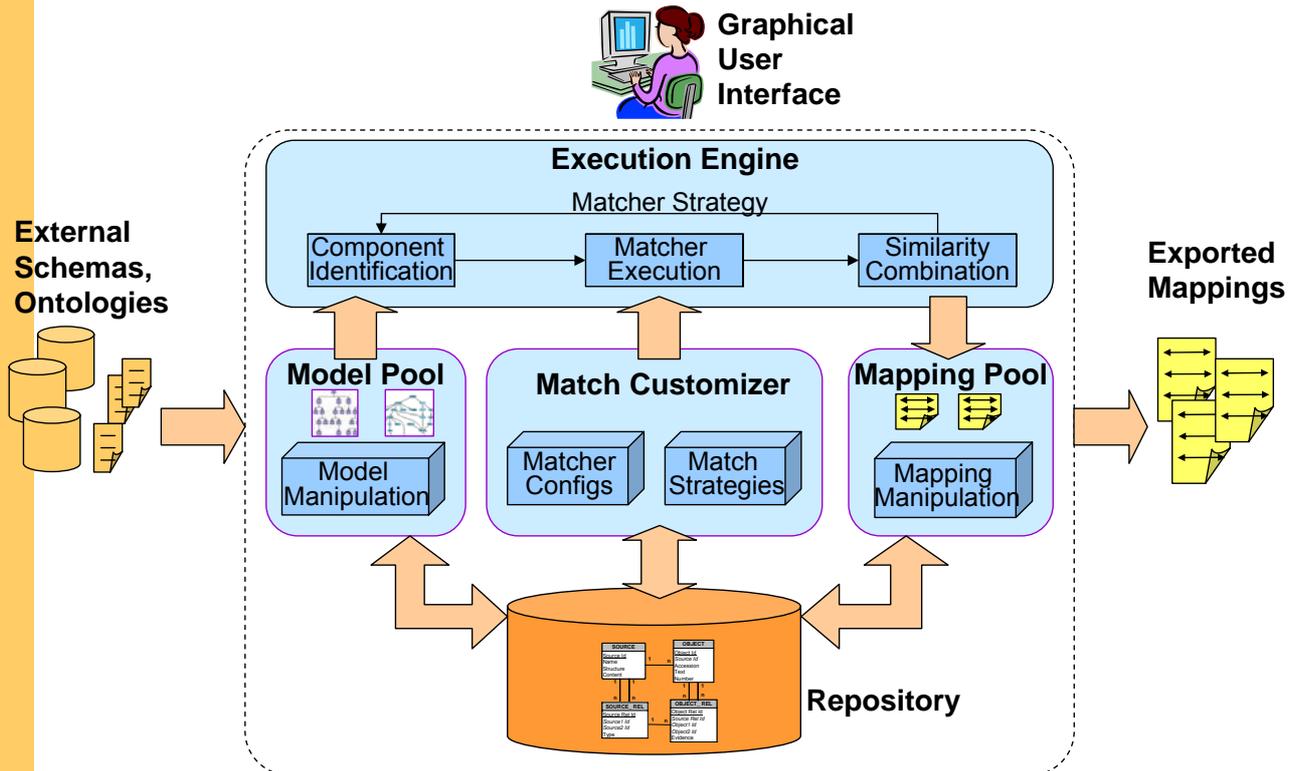
# Frameworks: PROMPT\*

- Framework for ontology alignment and merging
  - Plug-in tool for Protege 2000
- Linguistic matching
- Iterative user feedback and match result manipulation
  - Automatic detection of ontology conflicts
  - Interactive conflict resolution and automatic conflict resolution based on user-preferred ontology
- Merge operation: Create a new ontology or extend one selected ontology
  - Automatic creations of parent- and sub-concept relationships
  - Suggestions of similar concepts based on ontology matches

\*Noy, N.; Musen, M.: *PROMPT – Algorithm and tool for automated ontology merging and alignment*. Proc. Conf. on Artificial Intelligence and Innovative Applications of Artificial Intelligence, 2000.



# System Architecture\*



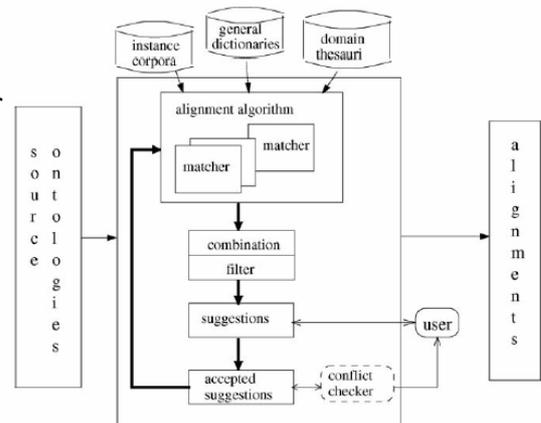
\*Do, H.H., E. Rahm: *COMA - A System for Flexible Combination of Schema Matching Approaches*. VLDB 2002

Aumüller D., H.-H. Do, S. Massmann, E. Rahm: *Schema and Ontology Matching with COMA++*. Sigmod 2005

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## Frameworks: SAMBO\*

- System for aligning and merging biomedical ontologies
- Framework to find similar concepts in overlapping ontologies for alignment and merge tasks
  - Import of OWL ontologies
  - Support of various match strategies by applying / combining different matchers and use of auxiliary information
    - Linguistic, structure-based, constraint-based, instance-based matcher
  - Iterative user feedback for match results
  - Result manipulation by description logic reasoner checking for ontology consistency, cycles, unsatisfiable concepts



\*Lambrix, P; Tan, H.: *SAMBO – A system for aligning and merging biomedical ontologies*. Journal of Web Semantics, 4(3):196-206, 2006.

## Metadata-based match approaches

- Metadata: Concept names, descriptions, ontology structure, ...
- Match mainly based on syntax and structure
- Limited use of domain knowledge
- Highly similar names with opposite semantics, e.g., ion vs. anion, organic vs. inorganic

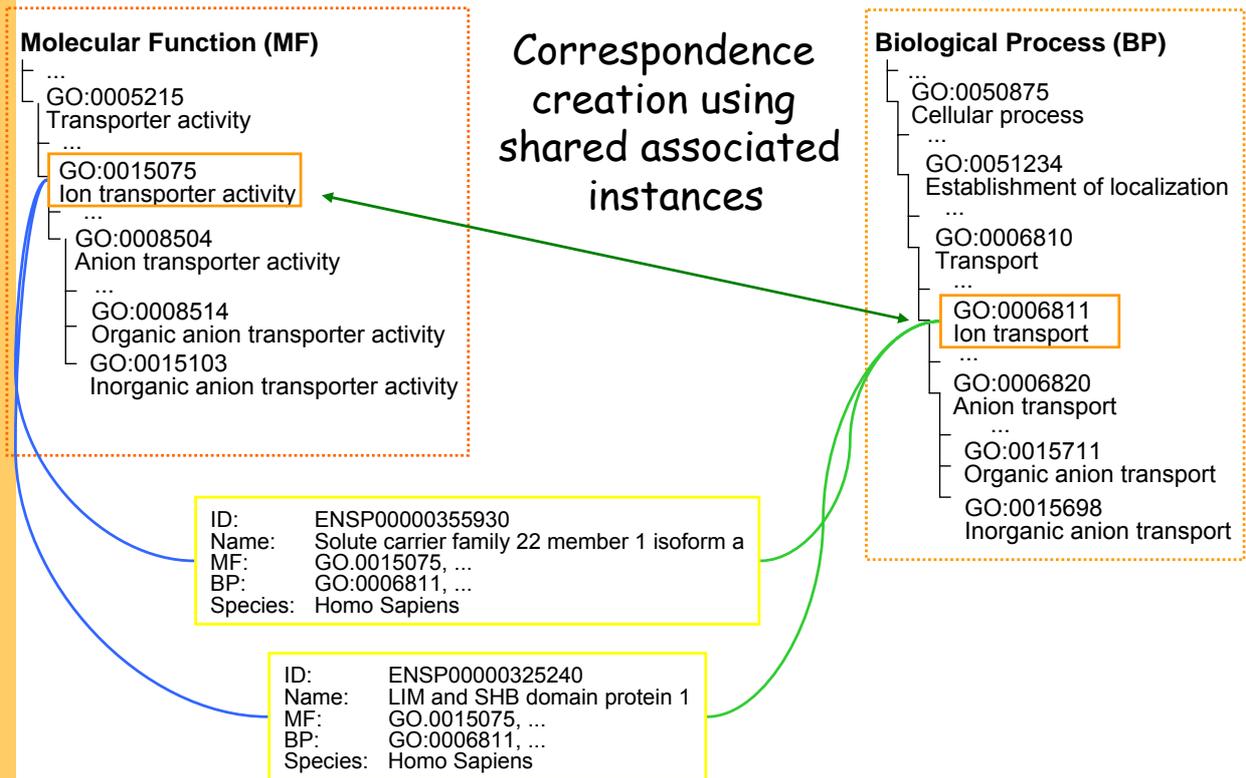
		Sim <sub>2-Gram</sub>
ion transporter	– anion transport	0.77
ion transporter activity	– ion transport	0.66

## Instance-based match approach\*

- Approach
  - Use domain-specific knowledge expressed in existing instance associations to create ontology mappings
- Key idea: "Two concepts are related if they share a significant number of associated objects"
- Flexible and extensible approach
  - Instance associations of pre-selected sources
  - Different metrics to determine the instance-based similarity
  - Combination of different ontology mappings

\* Kirsten, T, Thor, A; Rahm, E.: *Instance-based matching of large life science ontologies*. Proc. 4th Intl. Workshop DILS, July 2007

# Instance-based matching



# Selected similarity metrics

- Baseline similarity  $Sim_{Base}$

$$Sim_{Base}(c_1, c_2) = \begin{cases} 1 & \text{if } N_{c_1c_2} > 0 \\ 0 & \text{if } N_{c_1c_2} = 0 \end{cases}$$

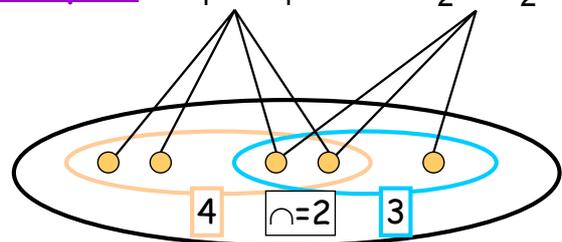
- Dice similarity  $Sim_{Dice}$

$$Sim_{Dice}(c_1, c_2) = \frac{2 \cdot N_{c_1c_2}}{N_{c_1} + N_{c_2}}$$

- Minimum similarity  $Sim_{Min}$

$$Sim_{Min}(c_1, c_2) = \frac{N_{c_1c_2}}{\min(N_{c_1}, N_{c_2})}$$

Example:  $c_1 \in O_1$        $c_2 \in O_2$



$$\begin{aligned} Sim_{Base} &= 1 \\ Sim_{Dice} &= 2 \cdot 2 / (4 + 3) = 0.57 \\ Sim_{Min} &= 2 / 3 = 0.67 \end{aligned}$$

$$0 \leq Sim_{Dice} \leq Sim_{Min} \leq Sim_{Base} \leq 1$$

## Evaluation metrics

- Computation of precision & recall needs a perfect mapping
  - Laborious for large ontologies
  - Might not be well-defined
- Metric *Match Coverage* to approximate "recall"
  - Idea: Measure fraction of matched concepts

$$MatchCoverage_{O_1} = \frac{|C_{O_1-Match}|}{|C_{O_1}|} \in [0...1] \quad Combined \quad InstMatchCoverage = \frac{|C_{O_1-Match}| + |C_{O_2-Match}|}{|C_{O_1-Inst}| + |C_{O_2-Inst}|} \in [0...1]$$

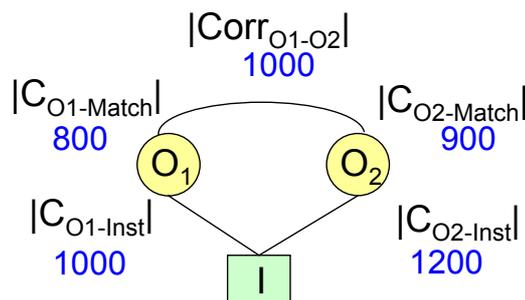
- Metric *Match Ratio* to approximate "precision"
  - Idea: Measure average number of match counter-parts per matched concept

$$MatchRatio_{O_1} = \frac{|Corr_{O_1-O_2}|}{|C_{O_1-Match}|} \geq 1 \quad CombinedMatchRatio = \frac{2 \cdot |Corr_{O_1-O_2}|}{|C_{O_1-Match}| + |C_{O_2-Match}|} \geq 1$$

- Goal: high Match Coverage with low Match Ratio

## Evaluation metrics cont.

- Example:



$$InstMatchCoverage_{O_1} = 800/1000 = 0.80$$

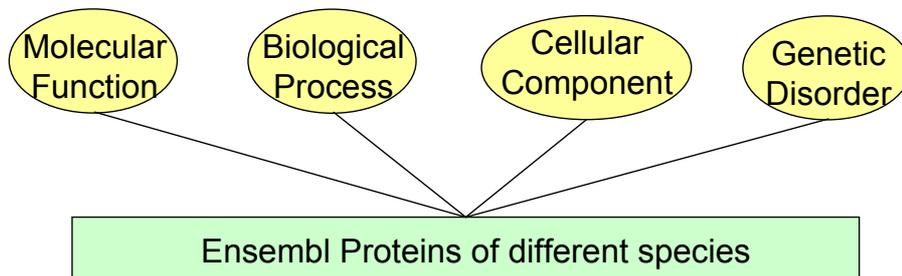
$$InstMatchCoverage_{O_2} = 900/1200 = 0.75$$

$$MatchRatio_{O_1} = 1000/800 = 1.25$$

$$MatchRatio_{O_2} = 1000/900 = 1.11$$

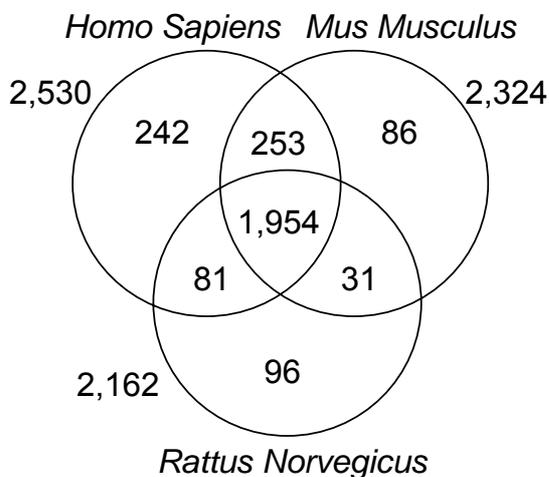
## Match scenario

- Ontologies
  - Subontologies of GeneOntology: Mol. function, biol. processes and cell. components
  - Genetic disorders of OMIM
- Instances: Ensembl proteins of different species, i.e., homo sapiens, mus musculus, rattus norvegicus



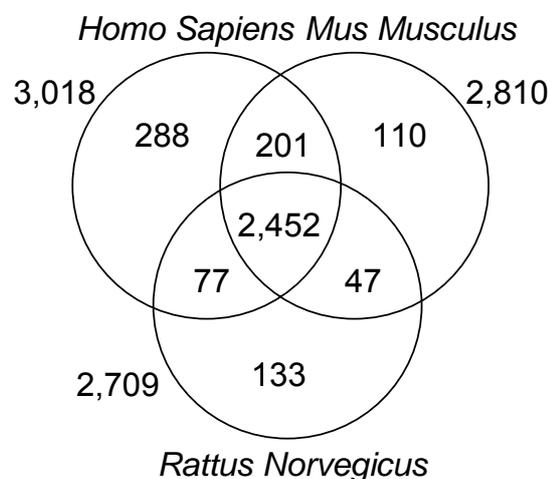
## Ontology overlap between species

Total # functions: 7,514



Number of associated  
Molecular Functions

Total # processes: 12,555



Number of associated  
Biological Processes

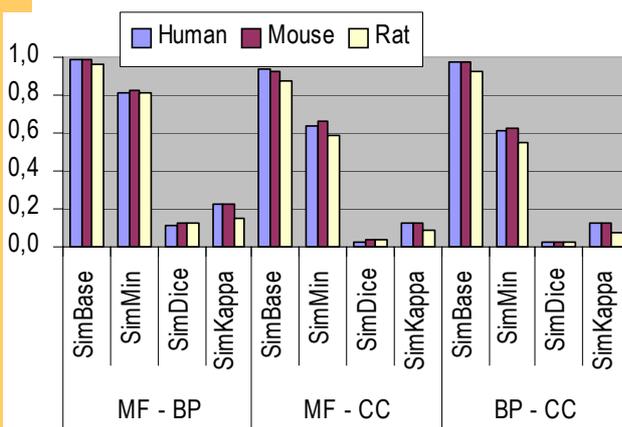
# Exhaustive match study

- Instance-based matching
  - Direct protein associations of human, mouse, rat
  - Study of match combinations: Union, intersection
  - Utilization of indirect associations
- (Simple) Metadata-based matching
  - Utilization of concept names
  - Trigram string similarity; different thresholds
- Comparison of instance- and metadata-based match results

# Match results: Direct instance associations

- Sim<sub>Base</sub>: High Coverage (99%), moderate to high Match Ratios
- Sim<sub>Dice</sub>: Very restrictive (Coverage < 20%) but low Match Ratios
- Sim<sub>Min</sub>: High Coverage (60%-80%) with high number of covered concepts but significantly lower Match Ratios than Sim<sub>Base</sub>

Combined Instance Coverage



Match Ratios per ontology

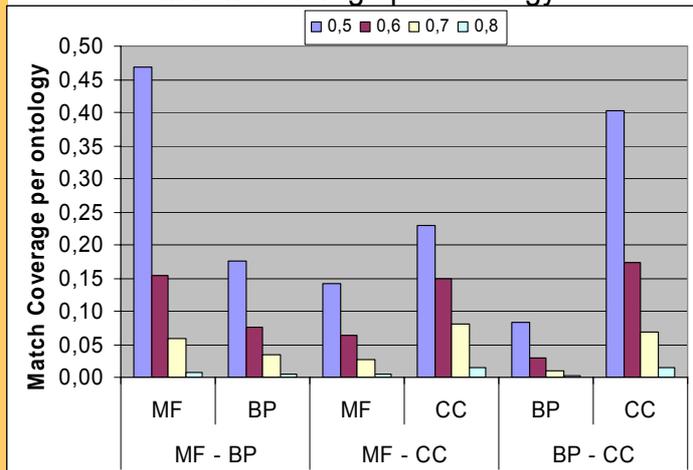
	MF - BP		MF - CC		BP - CC	
	MF	BP	MF	CC	BP	CC
Base	20.4	17.0	7.6	28.6	9.8	46.3
Min	4.4	4.0	2.2	7.8	2.4	8.6
Dice	1.3	1.2	1.0	1.3	1.0	1.3
Kappa	2.0	2.0	1.9	2.7	1.7	2.6

(Match Ratios for Homo Sapiens)

## Match results: Metadata-based matching

- Growing Coverage and Match Ratios for lower thresholds
- No correspondences with a similarity  $\geq 0.9$
- Moderate to low Match Ratios
- Inclusion of false positives for low thresholds, e.g. 0.5

Match Coverage per ontology

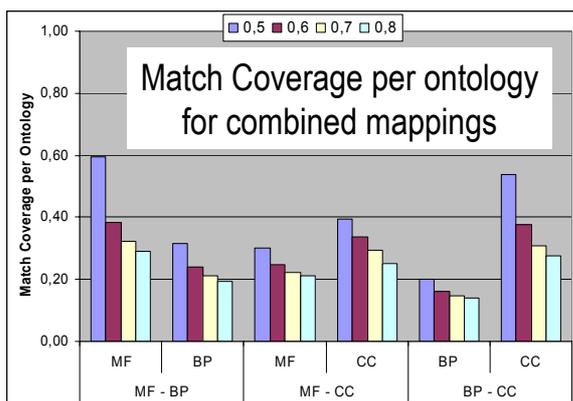


Match Ratios per ontology

	MF - BP		MF - CC		BP - CC	
	MF	BP	MF	CC	BP	CC
0.5	4.4	6.9	2.5	6.3	2.5	3.4
0.6	2.4	2.9	2.7	4.6	1.7	2.0
0.7	1.4	1.4	1.1	1.5	1.4	1.4
0.8	1.1	1.1	1.1	1.2	1.1	1.2

## Match results: Match combinations

- Combinations between instance- ( $Sim_{Min}$ ) and metadata-based match approach
  - Union: Increased coverage, higher influence of  $Sim_{Min}$  for increased thresholds of the metadata-based matcher
  - Intersection: Low Match Coverage (<1%) and Match Ratios
- Low overlap between instance- and metadata-based mappings



Match Ratios per ontology  
(threshold 0.7)

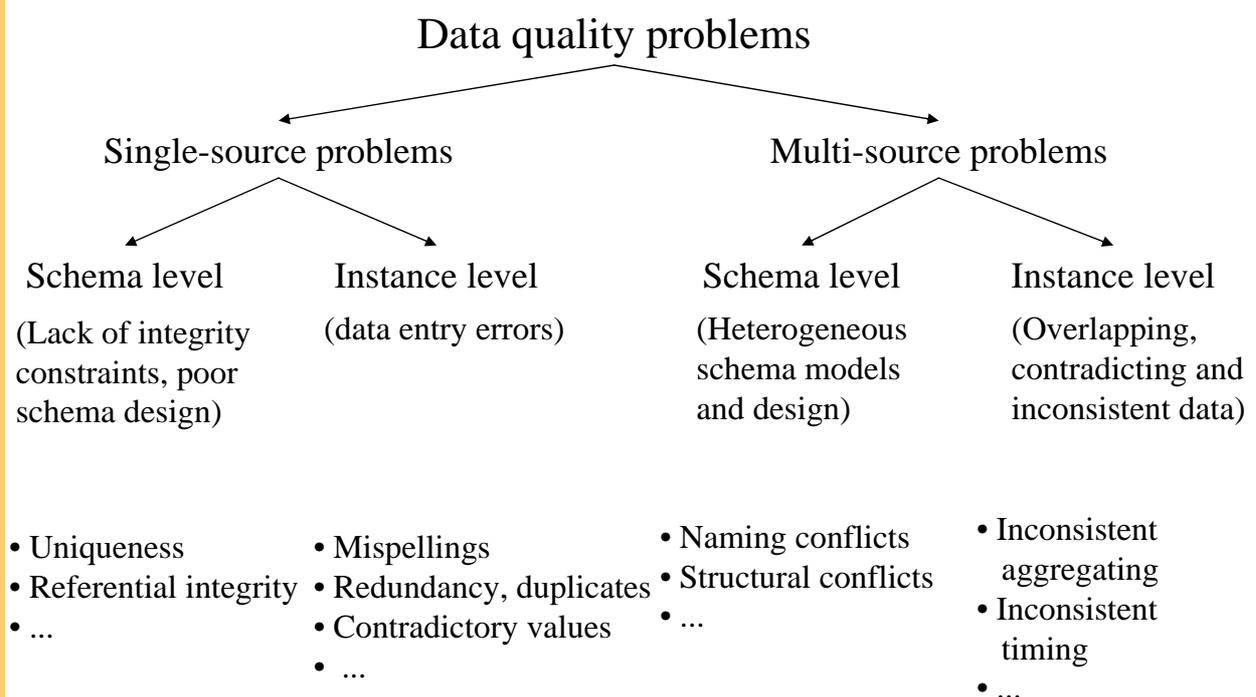
	MF - BP		MF - CC		BP - CC	
	MF	BP	MF	CC	BP	CC
$\cup$	4.1	3.7	2.2	6.7	2.4	7.6
$\cap$	1.0	1.0	1.0	1.0	1.0	1.3

( $Sim_{Min} = 1.0$ , Homo Sapiens)

# Agenda

- Kinds of data to be integrated
- General data integration alternatives
- Warehouse approaches
- Virtual and mapping-based data integration
- Data quality aspects
  - Overview and examples of quality problems
  - Object Matching
  - Data cleaning frameworks
- Conclusions and further challenges

# Overview\*



\*Rahm, E; Do, H.-H.: *Data cleaning: Problems and current approaches.*  
IEEE Techn. Bulletin on Data Engineering, 23(4), 2000

# Single-source problems

- Example: Protein data
- Causes
  - Schemaless storage, e.g., file-based data storage
  - Lack of input / acceptance integrity constraints
  - ...

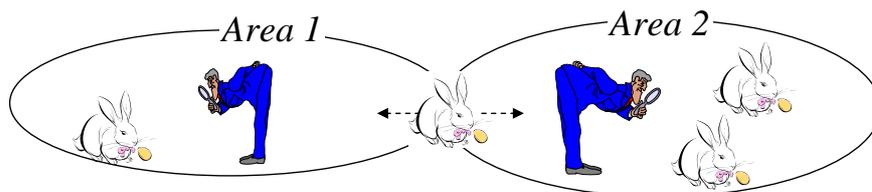
Accession	Entry-Name	Protein-Name	Species	Comment	Sequence
P68511	1433F_RAT	14-3- protein eta	Rat		MGDREQLL...
P11576	1433F_RAT	14-3- protein eta	Rattus norvegicus		mgdreqll...
P0A5B7	14KD_MYCTU	14 kDa antigen, also: 16kDa antigen, HSP16.3	Mycobacterium tuberculosis	[ENSEMBL: ENSP00007463]	

Annotations in the diagram:

- Uniqueness:** Points to the 'Accession' column.
- Synonyms:** Points to the 'Protein-Name' column.
- Case insensitivity:** Points to the 'Entry-Name' column.
- Multiple values:** Points to the 'Protein-Name' column.
- Encoding of further annotations and links:** Points to the 'Comment' column.
- Missing values:** Points to the 'Sequence' column.

# Multi-source problems (selection)

- Multiple experiments on same problem with different results
  - Different normalization and analysis methods
  - Human interpretation !
- Observations of mobile things, e.g., animals in bordering areas
  - Human observations
  - Varying annotations (difficult to be objective):
    - white-brown vs. brown-white, full vs. complete
  - Example: Describe and count animal populations



Nr	Colour	Pattern	...
1	snow-white	full	...
2	white-brown	spotted	...

Integration with object fusion

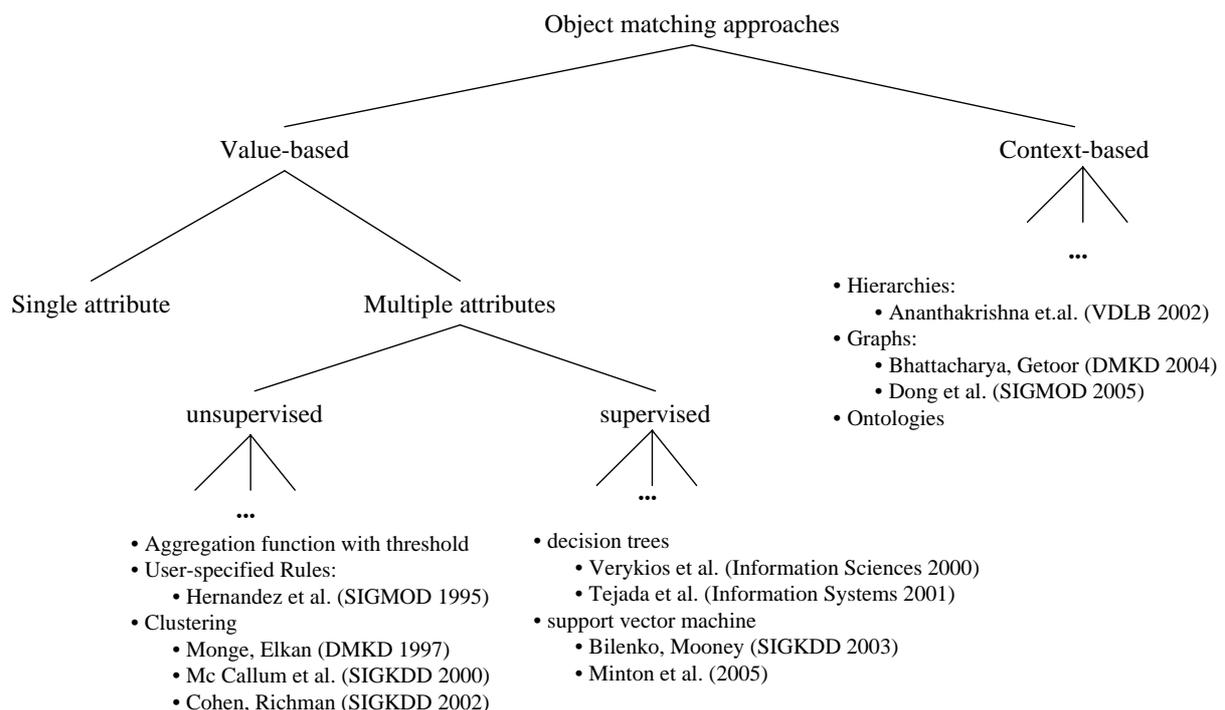
Nr	Colour	Pattern	...
1	white-brown	spotted	...
2	beige	complete	...
3	white	complete	...

# Simple solution strategies

- Uniqueness
  - Utilization of global identifiers
  - Use identifier mappings to a second source (of the same type and detail level)
- Multiple values / encodings
  - Extract atomic values by specific parsers, regular expressions
  - Normalization of dependent attributes
- Synonyms: Use available controlled vocabularies / ontologies as much as possible, e.g., NCBI Taxonomy for species
- Case insensitiveness: e.g. transform all values to upper/lower case

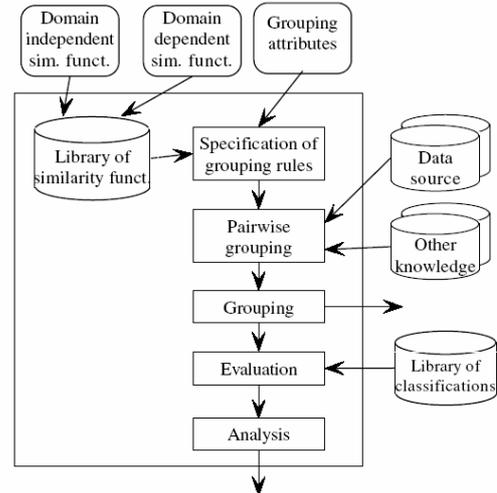
Accession	Entry-Name	Protein-Name	Species	Comment	Sequence
P68511	1433F_RAT	14-3- protein eta	Rat		MGDREQLL...
P11576	1433F_RAT	14-3- protein eta	Rattus norvegicus		mgdreqll...
P0A5B7	14KD_MYCTU	14 kDa antigen, also: 16kDa antigen, HSP16.3	Mycobacterium tuberculosis	[ENSEMBL: ENSP00007463 ]	

# Object matching approaches



# Similarity-based grouping\*

- Goal: Detect and group duplicate (very similar) data entries
- Sequential procedure
  - Specification of grouping rules: Which similarity functions (also combinations) for which attributes
  - Pairwise grouping: Computing the similarity and comparing data entries based on selected / specified grouping rules
  - Grouping of pairs of data entries into cliques based on
    - Total number of groups
    - Number of data entries in a group
    - Disjoint / overlapping groups
  - Analysis and evaluation of generated groupings



\*Jakoniene, V; Rundqvist, D.; Lambrix, P.: *A method for similarity-based groupig of biological data*. Proc. DILS, 2006

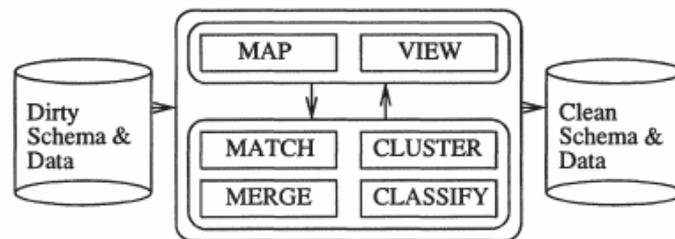
# Similarity-based grouping: Test cases

- Test: Group selected proteins into classes using
  - Annotations, e.g., attributes like product, definition
  - Protein sequences
  - Associations to GO ontology
- Results
  - Best grouping by using GO associations
  - Annotation-based: Too many groups
  - Sequence alignments: Too specific for grouping

Test case	Grouping rule	$n^e$	$n^g$	$n^c$	p	1-E	F	MI
1	$SemSim(GO_{ann}) > 0.95$ $GO_{ann}$ for component, process, function domains	71	23	24	0.90	0.93	0.88	0.86
2	$SemSim(GO_{ann}) > 0.95$	67	26	23	1.00	1.00	0.97	0.91
3	$SemSim(GO_{ann} + GO_{sw}) > 0.95$	75	23	24	0.80	0.87	0.79	0.79
4	$SemSim(GO_{ann} + GO_{ec}) > 0.95$	92	26	25	1.00	1.00	0.99	0.88
5	$SemSim(GO_{ann} + GO_{sw} + GO_{ec}) > 0.95$	93	26	25	0.86	0.93	0.88	0.81
6	$SemSim(GO_{ann} + GO_{sw} + GO_{ec}) > 0.95$ ; parent GO terms removed	93	26	25	0.86	0.93	0.88	0.81
7	$SemSim(GO_{ann}) > 0.95$ or $SemSim(GO_{sw}) > 0.95$ or $SemSim(GO_{ec}) > 0.95$	93	14	25	0.48	0.65	0.51	0.59
8	$SemSim(GO_{ann}) > 0.95$ or $SemSim(GO_{ec}) > 0.95$	92	26	25	1.00	1.00	0.99	0.88
9	$SemSim(GO_{ann} + GO_{ec}) = 1$	92	26	25	1.00	1.00	0.99	0.88
10	$SemSim(GO_{ann} + GO_{ec}) > 0.85$	92	21	25	0.70	0.78	0.71	0.68
11	$SemSim(GO_{ann} + GO_{ec}) > 0.95$ grouping algorithm: cliques	92	29	25	1.00	1.00	0.84	0.88
12	$EditDist(definition) > 0.9$ , for $GO_{ann} + GO_{ec}$	92	67	25	1.00	1.00	0.59	0.77
13	$EditDist(definition) > 0.7$ , for $GO_{ann} + GO_{ec}$	92	55	25	0.96	0.97	0.66	0.76
14	$SeqSim(sequence) > 0.85$ , for $GO_{ann} + GO_{ec}$	92	44	25	1.00	1.00	0.74	0.81
15	$EditDist(definition) > 0.85$	190	94	28	0.97	0.98	0.54	0.57
16	$EditDist(product) > 0.85$	190	105	28	0.99	0.99	0.49	0.57
17	$EditDist(definition) > 0.7$	190	68	28	0.81	0.87	0.56	0.50
18	$EditDist(product) > 0.7$	190	78	28	0.95	0.98	0.64	0.58
19	$EditDist(definition) > 0.9$ or $EditDist(product) > 0.9$ or $(EditDist(definition) > 0.6$ and $EditDist(product) > 0.6)$	190	64	28	0.94	0.96	0.70	0.58
20	$SeqSim(sequence) > 0.85$	190	59	28	0.99	0.99	0.66	0.62

# BIO-AJAX\*

- Framework for biological data cleaning
- Operators
  - MAP: translates the data from one schema to another schema.
  - VIEW: extracts portions of data for cleaning purposes.
  - MATCH: detects duplicate or similar records
  - MERGE: combines duplicate records or similar records into one record



\*Herbert, K.G.; Gehani, N.H.; Piel, W.H.; Wang, J.T.-L.; Wu, C.H.: *BIO-AJAX: An Extensible Framework for Biological Data Cleaning*. SIGMOD Record 33(2), 2004

# Further data cleaning frameworks

- Research prototypes
  - AJAX (Galhardas et al., VLDB 2001)
  - IntelliClean (Lee et al., SIGKDD 2000)
  - Potter's Wheel (Raman et al., VLDB 2001)
  - Febrl (Christen, Churches, PAKDD 2004)
  - TAILOR (Elfeky et al., Data Eng. 2002)
  - MOMA (Thor, Rahm, CIDR 2007)
- Commercial solutions
  - DataCleanser (EDD), Merge/Purge Library (Sagent/QM Software), MasterMerge (Pitnew Bowes) ...
  - MS SQL Server 2005: Data Cleaning Operators (Fuzzy Join / Lookup)

## Agenda

- Motivation
- General data integration alternatives
- Warehousing of large biological data collections
- Virtual integration of molecular-biological data
- Data quality aspects
- Matching large life science ontologies
- Conclusions and further challenges

## Overall conclusions

- Diverse data characteristics
  - Large amounts of experimental data produced by different chip technologies
  - Integration / management of clinical data
  - Huge amount of inter-connected web sources
  - High amount of text data
- Comprehensive standardization efforts needed: object ids / formats, preprocessing routines of chip data, shared vocabularies / ontologies
- Need to support explorative workflows across different sources
- Different data integration architectures needed
  - Data Warehousing
  - Virtual and mapping-based integration approaches
  - Combinations

## Overall conclusions cont.

- Warehousing for integration of large collections of biological data
  - Ideal for analysis / data mining on huge data sets, e.g. experimental chip data
  - Comprehensive data preprocessing
  - Support for consistent annotations needed
  - Integration of external data for enhanced analysis
- Mapping-based data integration (e.g., BioFuice)
  - Utilization of instance-level mappings to traverse between sources and fuse objects
  - Set-oriented navigation + structured queries + keyword search
  - Programmability / workflow orientation
- Ontology matching
  - Metadata vs. instance-based matching, combined approach
  - Key problem: validation of mappings by domain experts
  - More research needed

## Future challenges

- Clinical data management: many organizational issues, data privacy
- Bridging different workstyles and research goals: computers scientists vs. biologists vs. clinicians
- Make data integration easier and faster, e.g. by a mashup-like paradigm
  - Enable biologist/users to extract, clean, integrate and analyze data themselves
  - Make it easier to develop and use data-driven workflows
- Annotation and ontology management
  - Creation, evolution, matching, merging of ontologies
  - Utilization of generic and domain-specific approaches
- Data quality: object matching and fusion, provenance, ...
- Data integration in new application fields, e.g. systems biology
  - e.g., management of metabolic ~, regulatory pathways, protein-protein-interaction networks
  - Combination of data of wet-lab experiments with cell-based simulation (in silico experiments)

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