Data Stream Management Systems

- for Sensor Networks –

Vera Goebel
Department of Informatics, University of Oslo

- New Computing Paradigm?
- Sensor Networks
- What are DSMSs? (terms)
- Why do we need DSMSs? (applications)
- Concepts: Data Model, Query Processing, Windows
- Application Example: Medical Data Analysis with Esper

Historical Perspective of Computing

Mainframes

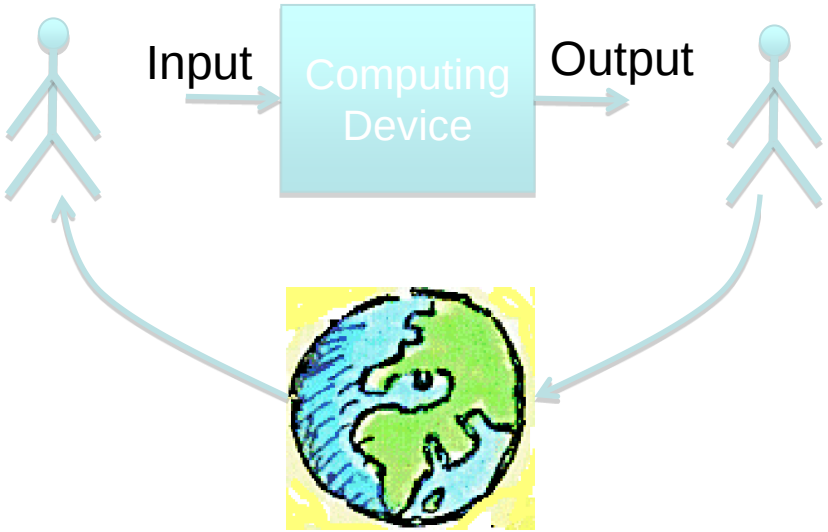
Perso
Comp

What is the common denominator?

Internet &
Mobile Computing

Today's Computing Paradigm

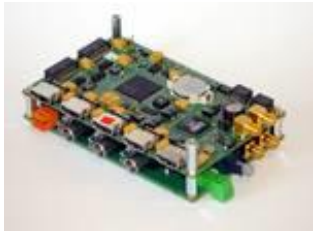
Device centric I/O



Human interaction, respectively human in the loop

Building Blocks for the Next Step …

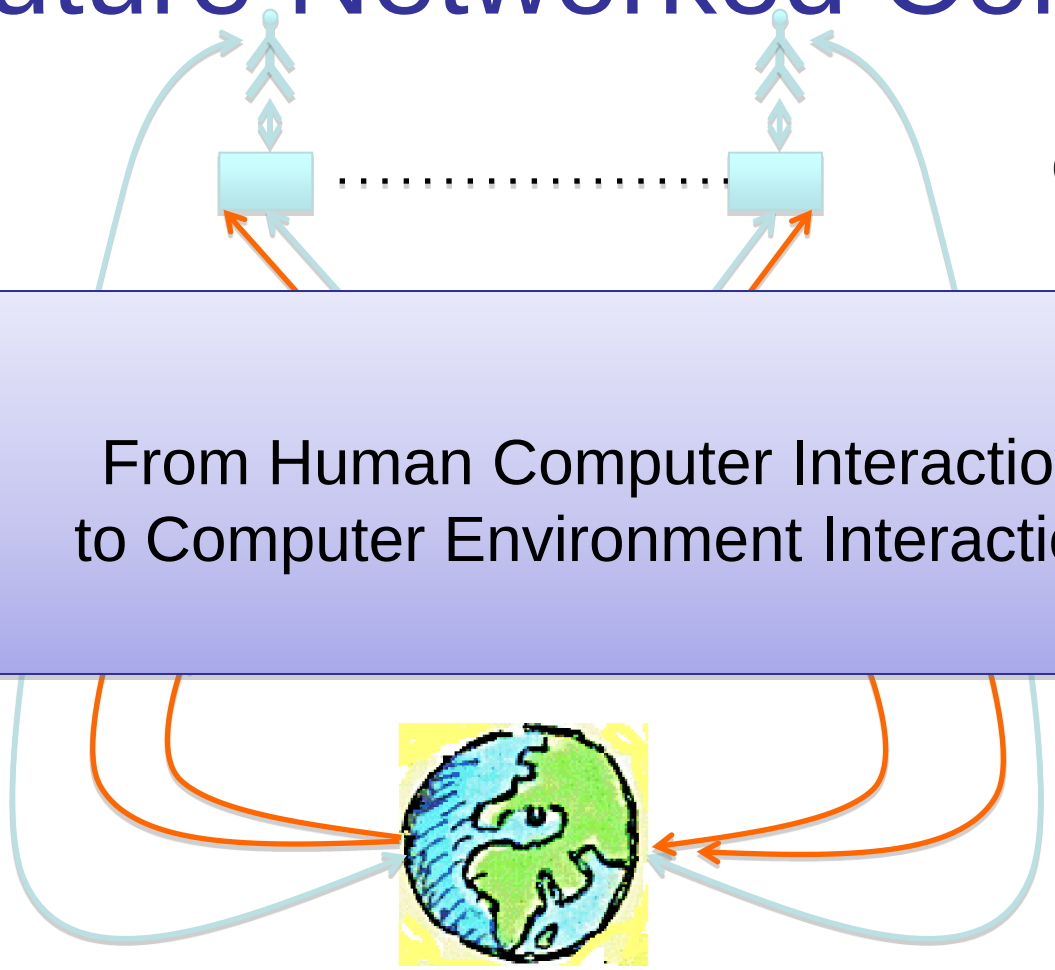
- Sensors



- Actuators

- Today very successful in specialized systems

Future Networked Computing



Networked computing devices, human interaction

From Human Computer Interaction (HCI)
to Computer Environment Interaction (CEI)

ting,
, potentially
eraction

Many Application Domains

Energy

- Automated Metering Infrastructure (AMI)
- Smart Grid

Manufacturing

- Automation & Decentralized Shop Floor Control
- Machine Maintenance

Transport and Logistics

- Track & Trace
- Supply Chain Integrity

Retail

- Customer Services / Retention
- Multi-Channel

Health

- Inclusion
- Assisted Living

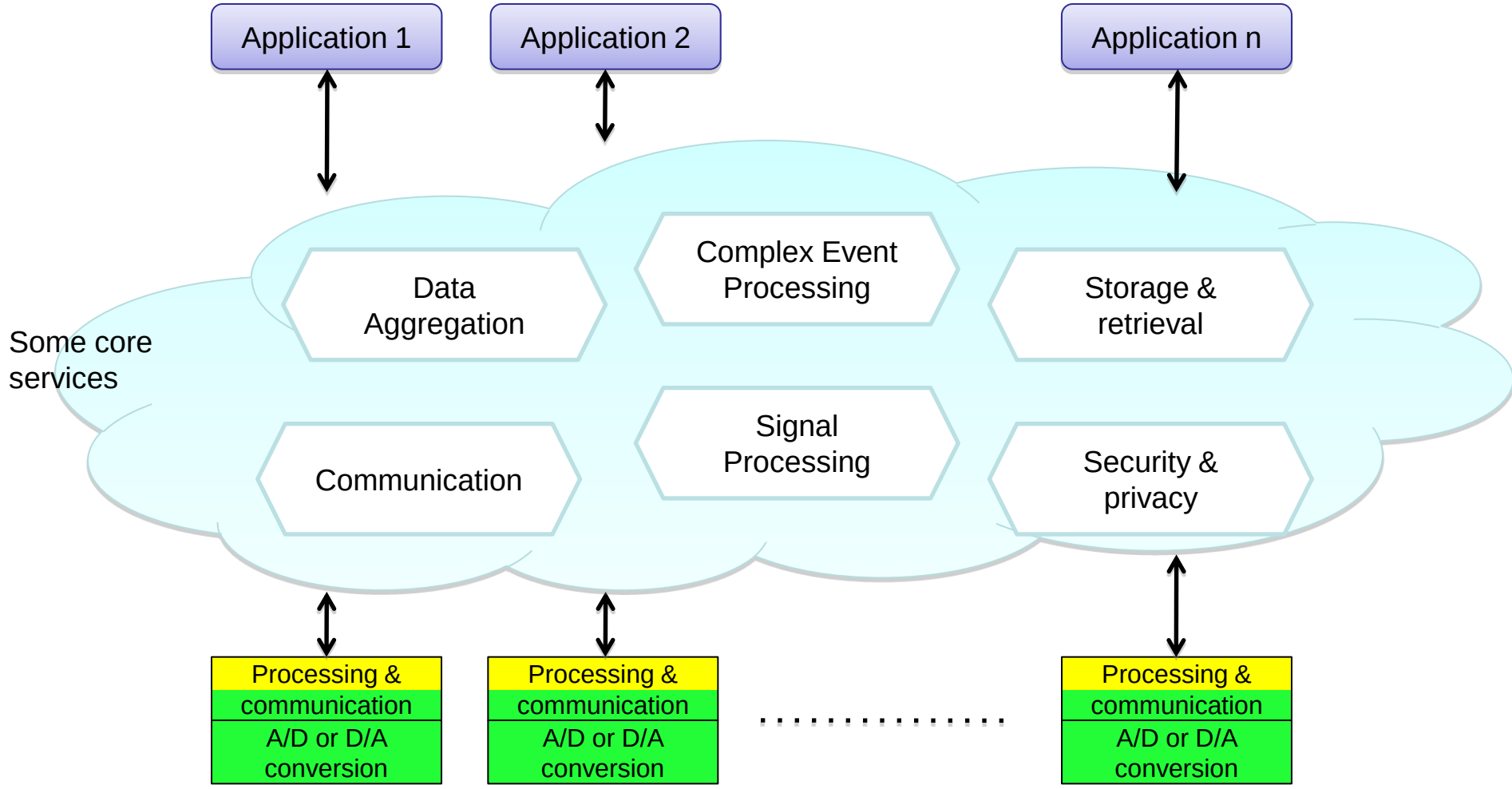
Automotive

- Car-to-X
- Vehicle Relationship Management

[T. Bohnert, SAP, June 2010]

Sensors and Actuators …

… seen from a system integrations point of view

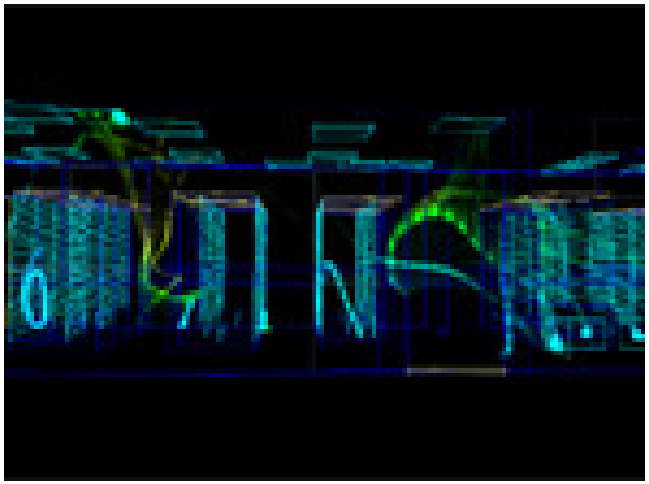


Some Sensornet Applications

ZebraNet

Redwood forest
microclimate monitoring

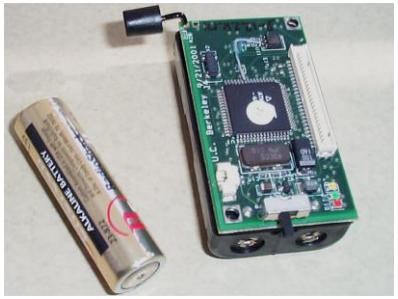
Smart cooling in data centers

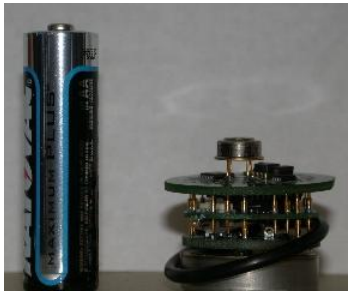


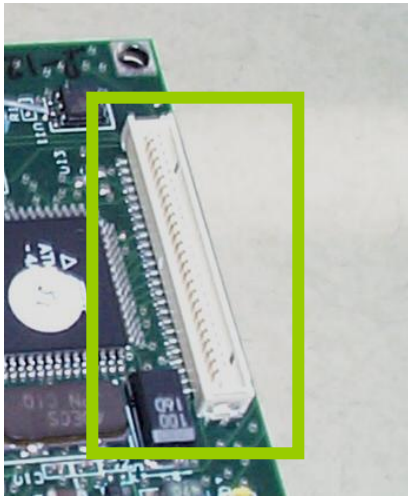
http://www.hpl.hp.com/research/dca/smart_cooling/

Sensor Hardware

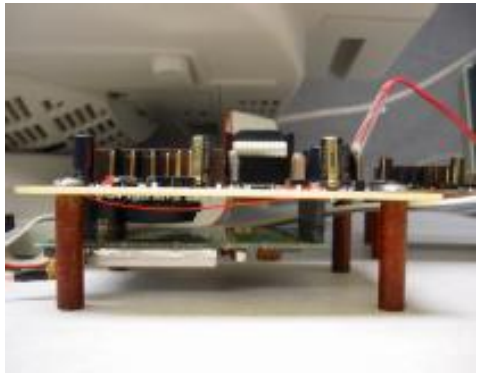
Motes:







ZebraNet II:



Principles of Sensor Networks

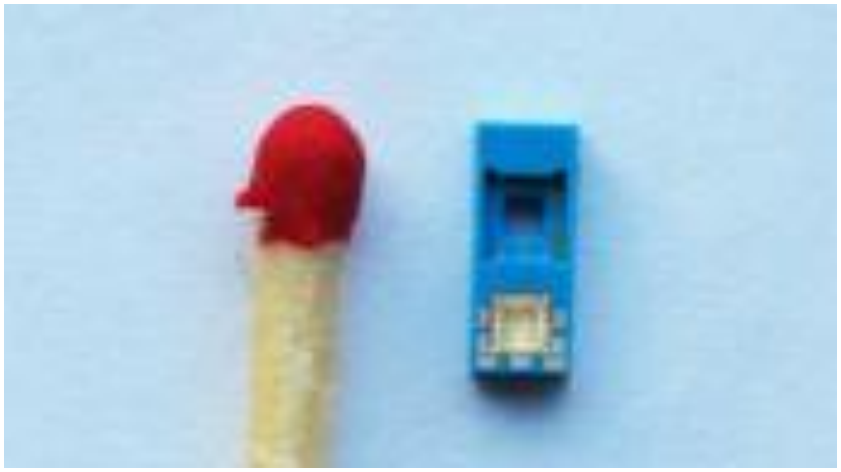
- A large number of low-cost, low-power, multifunctional, and small sensor nodes
- Sensor node consists of sensing, data processing, and communicating components
- A sensor network is composed of a large number of sensor nodes,
  - which are densely deployed either inside the phenomenon or very close to it.
- The position of sensor nodes need not be engineered or pre-determined.
  - sensor network protocols and algorithms must possess self-organizing capabilities.

Sensor Hardware

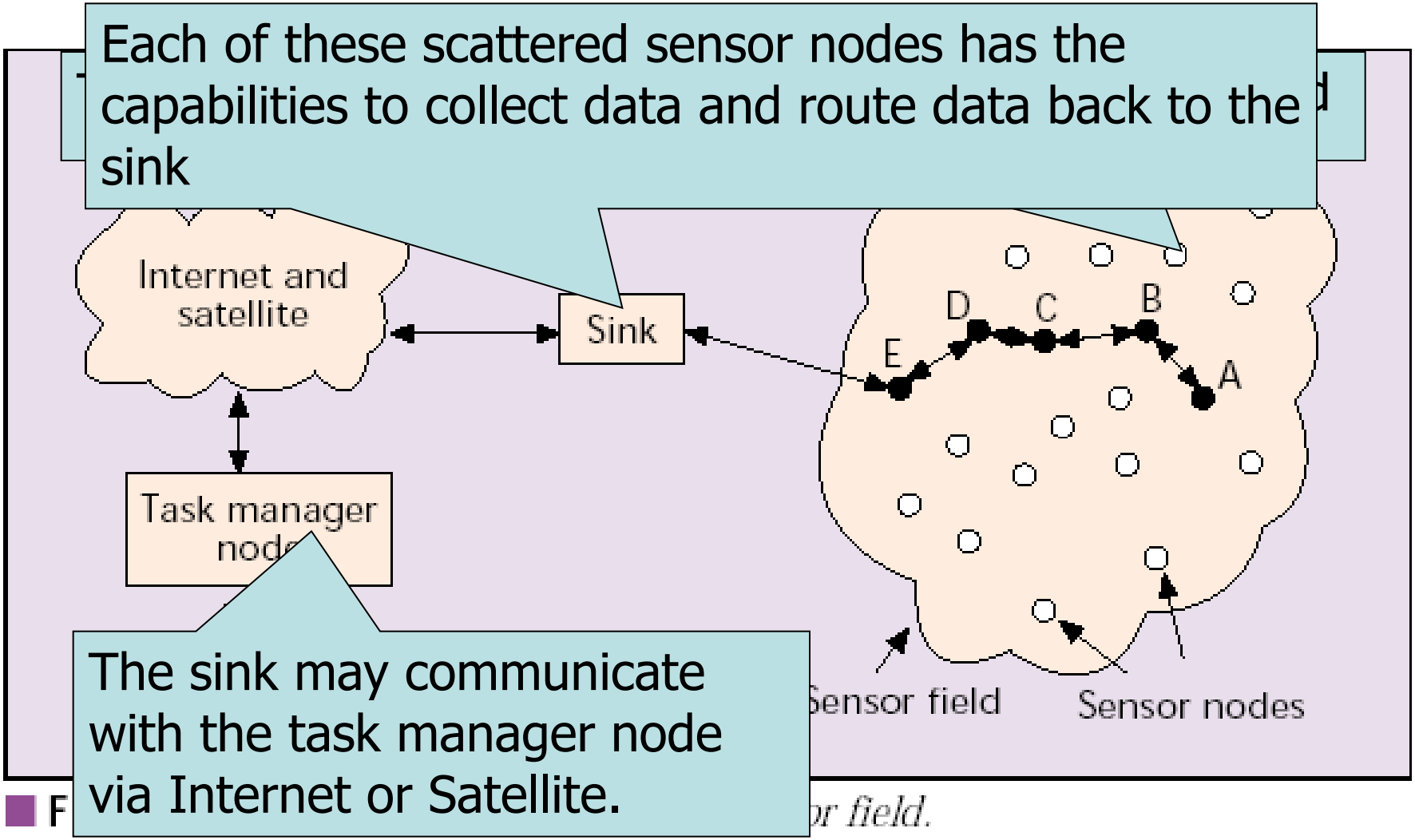
- A sensor node is made up of four basic components
  - a sensing unit
    - usually composed of two subunits: sensors and analog to digital converters (ADCs).
  - processing unit,
    - Manages the procedures that make the sensor node collaborate with the other nodes to carry out the assigned sensing tasks.
  - A transceiver unit
    - Connects the node to the network.
  - Power units (the most important unit)
- Matchbox-sized module
  - consume extremely low power,
  - operate in high volumetric densities,
  - have low production cost and be dispensable,
  - be autonomous and operate unattended,
  - be adaptive to the environment.

But we can better at Ifi ☺

GlucoSense project:
- Philipp Häfliger (NANO) and other external partners:
-Implanted sensor to measure blood sugar -> must be VERY small
-How to change the batteries?
-How to communicate?



Classical sensor networks architecture



- F … *or field.*

Sensor networks - issues

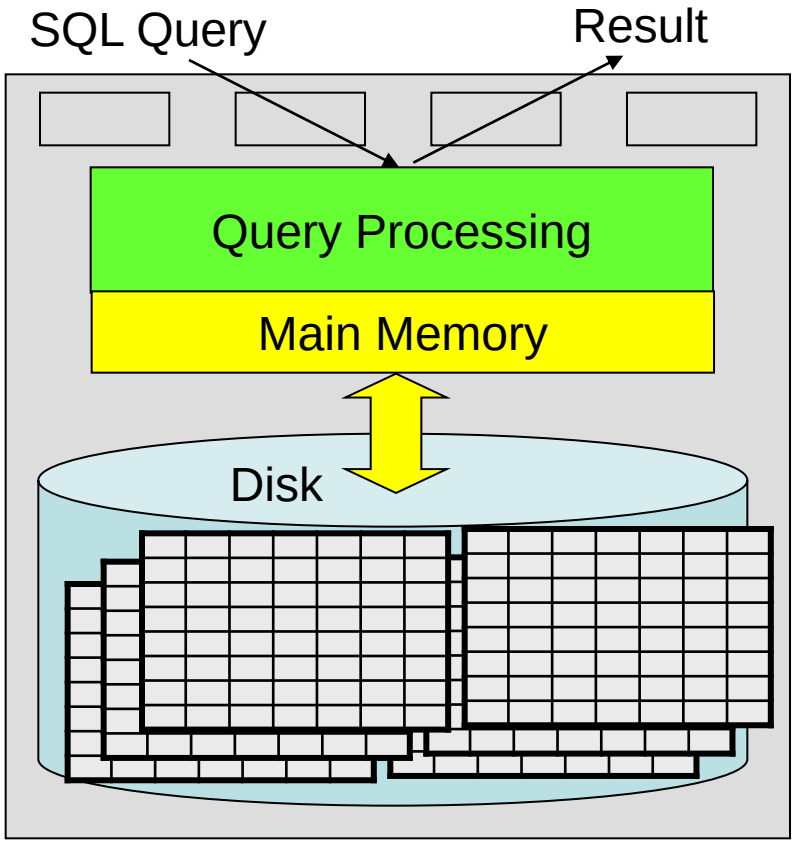
- Wireless sensors:
  - Small to ultra-small
  - Energy is very important
- Smart-phones
  - Everybody has one
  - Energy less important
  - Privacy
- Wired sensors
  - Surveillance cameras etc.
  - Energy is no problem
  - How to model multimedia data streams?

Opportunistic sensor networks

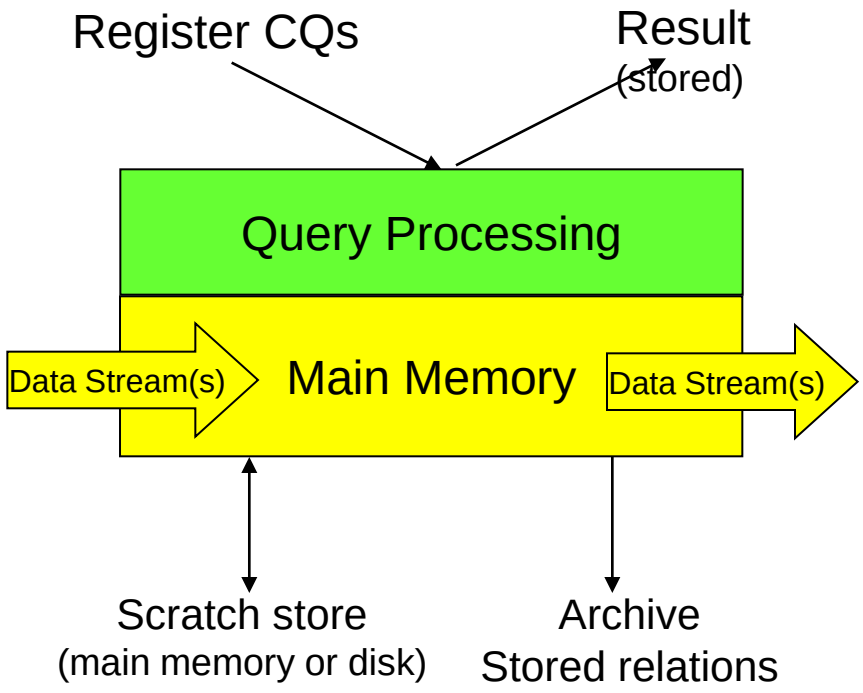
- What if we have networking problems?
  - Sensor nodes in sleep to save power
  - Mobility
  - Obstacles
  - +++
- Let’s see what the Future Internet should provide

Handle Data Streams in DBS?

Traditional DBS



DSMS



Data Management:
Comparison - DBS versus DSMS

Database Systems (DBS)

- Persistent relations
  (relatively static, stored)
- One-time queries
- Random access
- “Unbounded” disk store
- Only current state matters
- No real-time services
- Relatively low update rate
- Data at any granularity
- Assume precise data
- Access plan determined by query processor, physical DB design

DSMS

- Transient streams
  (on-line analysis)
- Continuous queries (CQs)
- Sequential access
- Bounded main memory
- Historical data is important
- Real-time requirements
- Possibly multi-GB arrival rate
- Data at fine granularity
- Data stale/imprecise
- Unpredictable/variable data arrival and characteristics

Adapted from [Motawani: PODS tutorial]

DSMS Applications

- Sensor Networks:
  - Monitoring of sensor data from many sources, complex filtering, activation of alarms, aggregation and joins over single or multiple streams
- Network Traffic Analysis:
  - Analyzing Internet traffic in near real-time to compute traffic statistics and detect critical conditions
- Financial Tickers:
  - On-line analysis of stock prices, discover correlations, identify trends
- On-line auctions
- Transaction Log Analysis, e.g., Web, telephone calls, …

Motivation for DSMS

- Large amounts of interesting data:
  - deploy transactional data observation points, e.g.,
    - AT&T long-distance: ~300M call tuples/day
    - AT&T IP backbone: ~10B IP flows/day
  - generate automated, highly detailed measurements
    - NOAA: satellite-based measurement of earth geodetics
    - Sensor networks: huge number of measurement points
- Near real-time queries/analyses
  - ISPs: controlling the service level
  - NOAA: tornado detection using weather radar data

Motivation for DSMS (cont.)

- Performance of disks:

	1987	**2004**	**Increase**
CPU Performance	1 MIPS	2,000,000 MIPS	2,000,000 x
Memory Size	16 Kbytes	32 Gbytes	2,000,000 x
Memory Performance	100 usec	2 nsec	50,000 x
Disc Drive Capacity	20 Mbytes	300 Gbytes	15,000 x
Disc Drive Performance	**60 msec**	**5.3 msec**	**11 x**

Source: Seagate Technology Paper: ” Economies of Capacity and Speed: Choosing the most cost-effective disc drive size and RPM to meet IT requirements”

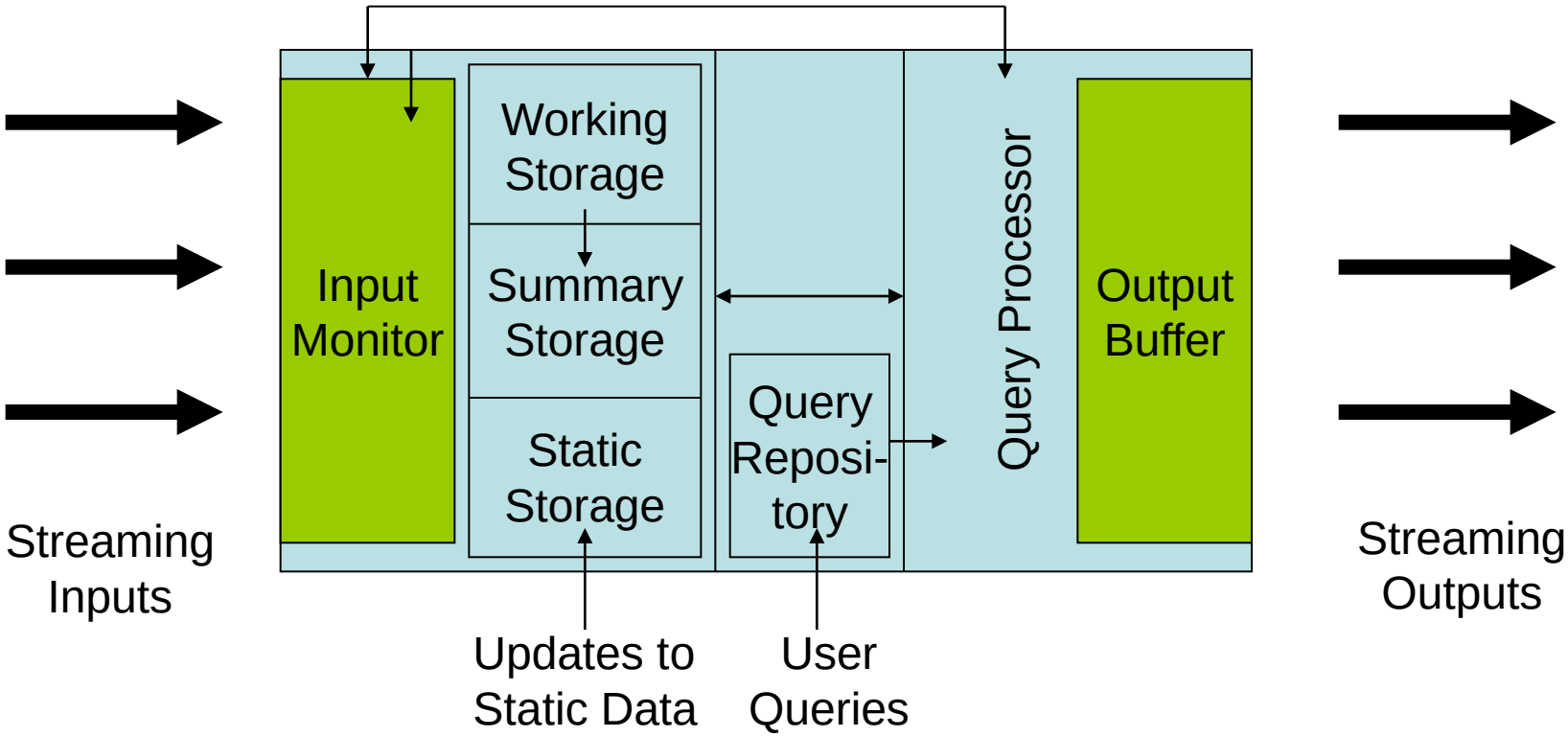
Motivation for DSMS (cont.)

- Take-away points:
  - Large amounts of raw data
  - Analysis needed as fast as possible
  - Data feed problem

Application Requirements

- Data model and query semantics: order- and time-based operations
  - Selection
  - Nested aggregation
  - Multiplexing and demultiplexing
  - Frequent item queries
  - Joins
  - Windowed queries
- Query processing:
  - Streaming query plans must use non-blocking operators
  - Only single-pass algorithms over data streams
- Data reduction: approximate summary structures
  - Synopses, digests => no exact answers
- Real-time reactions for monitoring applications => active mechanisms
- Long-running queries: variable system conditions
- Scalability: shared execution of many continuous queries, monitoring multiple streams
- Stream Mining

Generic DSMS Architecture



[Golab & Özsu 2003]

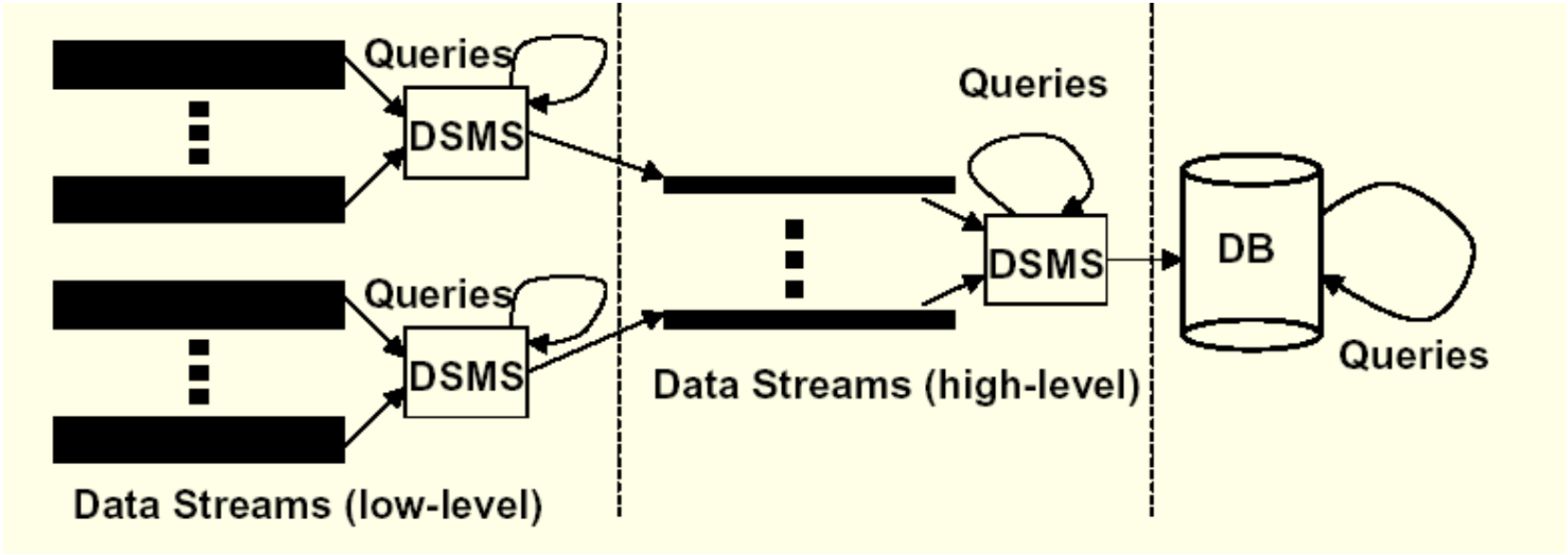
DSMS: 3-Level Architecture

DBS

- Data feeds to database can also be treated as data streams
- Resource (memory, disk, per-tuple computation) rich
- Useful to audit query results of DSMS
- Supports sophisticated query processing, analyses

DSMS

- DSMS at multiple observation points, (voluminous) streams-in, (data reduced) streams-out
- Resource (memory, per tuple computation) limited, esp. at low-level
- Reasonably complex, near real-time, query processing
- Identify what data to populate in DB



Data Models

- Real-time data stream: sequence of data items that arrive in some order and may be seen only once.
- Stream items: like relational tuples
  - relation-based models, e.g., STREAM, TelegraphCQ; or instanciations of objects
  - object-based models, e.g., COUGAR, Tribeca
- Window models:
  - Direction of movement of the endpoints: fixed window, sliding window, landmark window
  - Physical / time-based windows versus logical / count-based windows
  - Update interval: eager (update for each new arriving tuple) versus lazy (batch processing -> jumping window), non-overlapping tumbling windows

Timestamps

- Explicit
  - Injected by data source
  - Models real-world event represented by tuple
  - Tuples may be out-of-order, but if near-ordered can reorder with small buffers
- Implicit
  - Introduced as special field by DSMS
  - Arrival time in system
  - Enables order-based querying and sliding windows
- Issues
  - Distributed streams?
  - Composite tuples created by DSMS?

Queries - I

- DBS: one-time (transient) queries
- DSMS: continuous (persistent) queries
  - Support persistent and transient queries
  - Predefined and ad hoc queries (CQs)
  - Examples (persistent CQs):
    - Tapestry: content-based email, news filtering
    - OpenCQ, NiagaraCQ: monitor web sites
    - Chronicle: incremental view maintenance
- Unbounded memory requirements
- Blocking operators: window techniques
- Queries referencing past data

Queries - II

- DBS: (mostly) exact query answer
- DSMS: (mostly) approximate query answer
  - Approximate query answers have been studied:
    - Synopsis construction: histograms, sampling, sketches
    - Approximating query answers: using synopsis structures
    - Approximate joins: using windows to limit scope
    - Approximate aggregates: using synopsis structures
- Batch processing
- Data reduction: sampling, synopses, sketches, wavelets, histograms, …

One-pass Query Evaluation

- DBS:
  - Arbitrary data access
  - One/few pass algorithms have been studied:
    - Limited memory selection/sorting: *n*-pass quantiles
    - Tertiary memory databases: reordering execution
    - Complex aggregates: bounding number of passes
- DSMS:
  - Per-element processing: single pass to reduce drops
  - Block processing: multiple passes to optimize I/O cost

Query Languages

3 querying paradigms for streaming data:

1. Relation-based: SQL-like syntax and enhanced support for windows and ordering, e.g., Esper, CQL (STREAM), StreaQuel (TelegraphCQ), AQuery, GigaScope
2. Object-based: object-oriented stream modeling, classify stream elements according to type hierarchy, e.g., Tribeca, or model the sources as ADTs, e.g., COUGAR
3. Procedural: users specify the data flow, e.g., Aurora, users construct query plans via a graphical interface

(1) and (2) are declarative query languages,
currently, the relation-based paradigm is mostly used.

Approximate Query Answering Methods

- Sliding windows
  - Only over sliding windows of *recent stream data*
  - Approximation but often more desirable in applications
- Batched processing, sampling and synopses
  - Batched if update is fast but computing is slow
    - Compute periodically, not very timely
  - Sampling if update is slow but computing is fast
    - Compute using sample data, but not good for joins, etc.
  - Synopsis data structures
    - Maintain a small *synopsis* or *sketch* of data
    - Good for querying historical data
- Blocking operators, e.g., sorting, avg, min, etc.
  - Blocking if unable to produce the first output until seeing the entire input

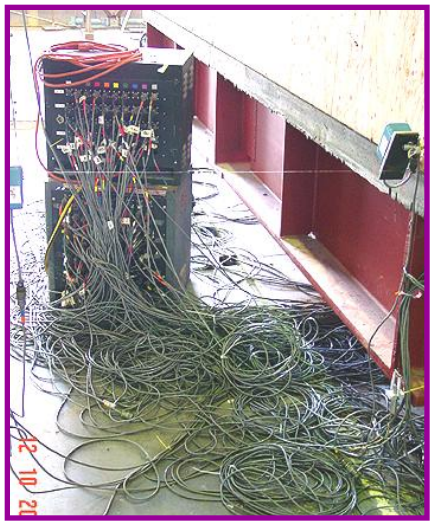
[Han 2004]

Application Examples

Habitat Monitoring: Storm petrels on Great Duck Island, microclimates on James Reserve.

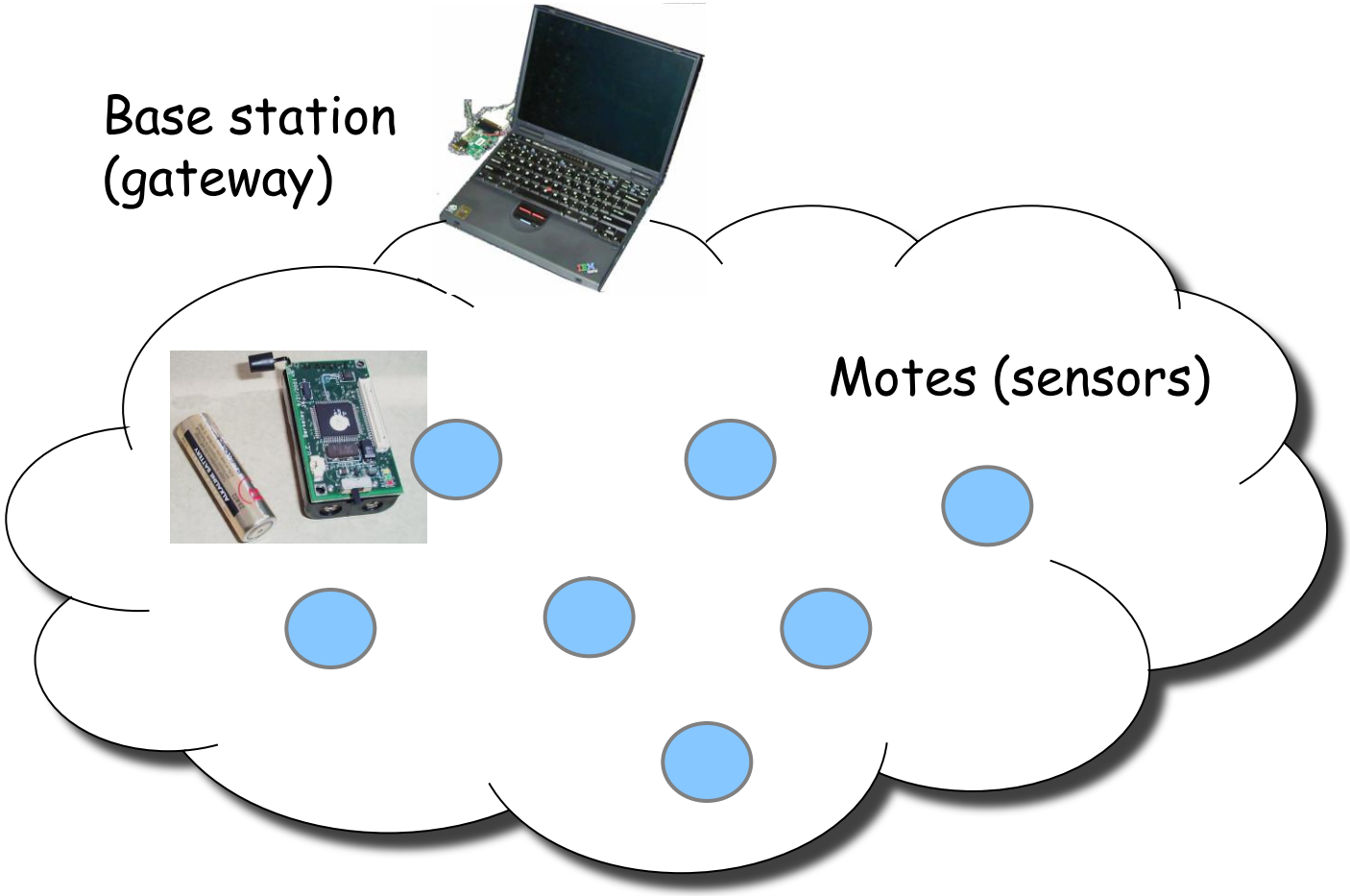
Earthquake monitoring in shake-test sites.

Vehicle detection: sensors along a road, collect data about passing vehicles.



Traditional monitoring apparatus.

Sensor Networks



Sensor Network Characteristics

- Autonomous nodes
  - Small, low-cost, low-power, multifunctional
  - Sensing, data processing, and communicating components
- Sensor network is composed of large number of sensor nodes
  - Proximity to physical phenomena
    - Deployed inside the phenomenon or very close to it
- Monitoring and collecting physical data
- No human interaction for weeks or months at a time
  - Long-term, low-power nature

Sensor Hardware

- A sensor node is made up of four basic components
  - Sensing unit
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Managing Data

- **Purpose of sensor network:**
  Obtain real-world data
  - Extract and combine data from the network

- **But:** Programming sensor networks is hard!
  - Months of lifetime required from small batteries
  - Lossy, low-bandwidth, short range communication
  - Highly distributed environment
  - Application development
  - Application deployment administration

Data Management Systems for Sensor Networks

- Motivation:
  - Implement data access
    - Sensor tasking
    - Data processing
    - Possibly support for data model and query language
- Goals:
  - Adaptive
    - Network conditions
    - Varying/unplanned stimuli
  - Energy efficient
    - In-network processing
    - Flexible tasking
    - Duty cycling

DSMS for Sensor Networks

- Aurora & Medusa System
  - Aurora: single-site high performance stream processing engine
  - Aurora*: connecting multiple Aurora workflows in a distributed environment
  - Medusa: distributed environment where hosts belong to different organizations and no common QoS notion is feasable
- TinyDB
  - Developed as public-domain system at UC Berkeley
  - Widely used by research groups as well as industry pilot projects
  - Successful deployments in Intel Berkeley Lab and redwood trees at UC Botanical Garden

Health Care Applications

- Integrated patient monitoring
- Telemonitoring of human physiological data
- Tracking and monitoring doctors and patients inside a hospital
- Tracking and monitoring patients and rescue personnel during rescue operations

Online Analysis of Myocardial Ischemia From Medical Sensor Data Streams with Esper

Stig Støa[1], Morten Lindeberg[2], Vera Goebel[2]

[1] The Interventional Centre (IVS), Rikshospitalet University Hospital, Oslo, Norway
[2] Distributed Multimedia Systems, Department of Informatics, University of Oslo, Norway

Adaptive Sized Windows To Improve Real-Time Health Monitoring – A Case Study on Heart Attack Prediction

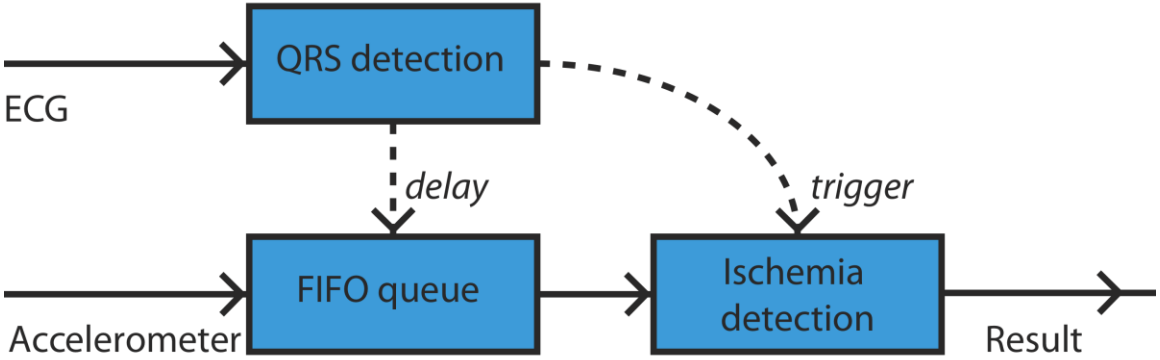
- **Application**: Real-time health monitoring.
- **Problem:** Data stream management systems (DSMSs) mainly support the processing of data stream windows of static size. Should adapt to the physiological processes of the human body, e.g., the cardiac cycle, which has variable durations.
- **Goal:** Adapt the processing of data streams to physiological processes, such as heartbeats, using *time-based sliding windows of adaptive "size."*

- Published work in biomedical symposium:

  Stig Støa, Morten Lindeberg, Vera Goebel: Online Analysis of Myocardial Ischemia from Medical Sensor Data Streams with Esper, *Proceedings of the First International Symposium on Applied Sciences in Biomedical and Communication Technologies (ISABEL 2008), October 2008*

Idea

- Let external events (tuple results from external query) determine the window size of a sliding window
- ECG stream to detect heartbeats (*QRS detection)*
- Accelerometer stream to detect heart displacement (*Ischemia detection)*
- Output of *QRS detection (delay) determines when to trigger the flushing of the sliding window in Ischemia detection query*
- 'Delay' is used to slow down accelerometer stream to account for QRS detection delay in the *FIFO queue*



Experiment Goal #1

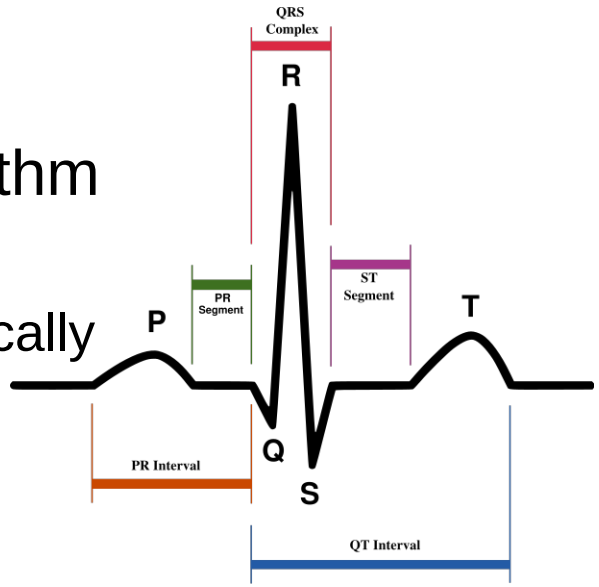
- Recreate off-line technique (Elle et al. 2005) conducted in MATLAB
- Early recognition of regional cardiac ischemia
- 3-way accelerometer placed on left ventricle of the heart

- *Single metric:*
  - Fast Fourier Transformation (FFT) is used to examine the accelerometer signal in the frequency-domain
  - Euclidian distance vector (**EDV(i)**) between reference vector **RV(0)** and current vector **CV(j)**, where **j** is the latest sample number
  - **CV(j)** : FFT over sliding window (size 512 over y-axis)
  - **RV(0)** : FFT over baseline window (first 512 samples)

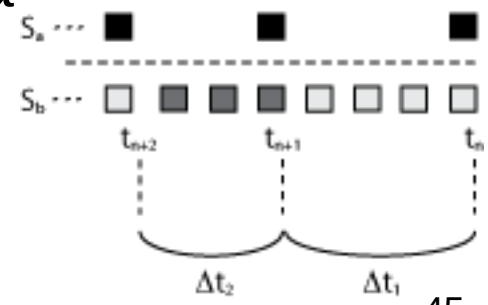
- Data set from surgery performed on pigs at the Interventional Centre
- We can conduct experiments with the same data set (*data set 1*)

Experiment Goal #2

- Improve results by adding beat-to-beat detection using a QRS detection algorithm on ECG signals
  - Each ECG trace of a normal heartbeat typically contains a QRS event
  - A good reference for separating heartbeats
- We need to perform FFT over sliding windows of variable size!
- Cannot use the same data, use new data set that include ECG (*data set 2*)



[image from http://www.wikipedia.org]



Challenges

1. Incorporate signal processing operations
   - Problem: Not supported in the query language
   - Fast Fourier Transformation of the accelerometer signals
   - Euclidian distance vector from baseline window
   - QRS detection for detecting the heartbeats from the ECG signals
   - Solution: Custom aggregate functions

2. Static sized windows are not feasible for beat-to-beat detection
   - Problem: Heartbeat duration is not a static pre-known size. DSMS window techniques only describe static time-based or tuple-based windows.
   - Solution: Introduce variable length triggered tumbling windows

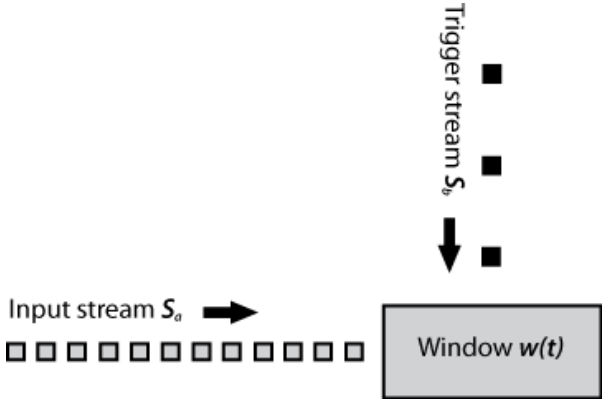
3. Synchronize the two streams
   - Problem: QRS detection introduces variable delay (approx. 91 samples)
   - Solution: Introduce variable buffer, that “slows” down the accelerometer stream

Signal processing operations

- Implement as custom aggregate functions
- Use defined Java interface and simply add to query engine
- Implemented methods:
  - **QRSD(v):** QRS detection based on algorithm from Hamilton et al. 1986, source code is public available
  - **edv(v):** Euclidian distance from baseline

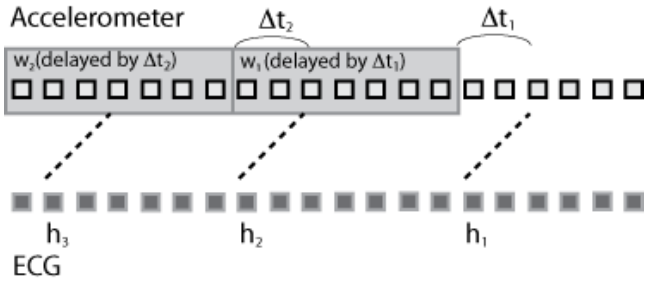
Variable length triggered tumbling windows

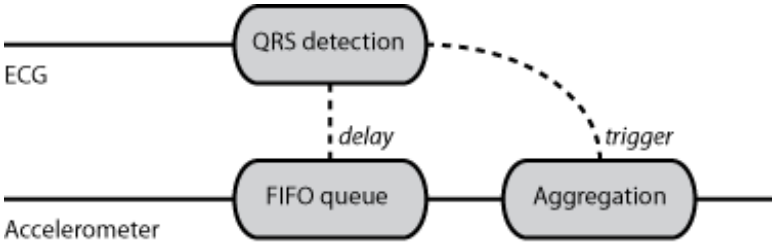
- The ECG stream is aggregated into a stream consisting of QRS events S_b.
- This stream (S_b) triggers the flushing of the sliding window ***w(t)*** where the custom aggregation over the stream S_a is performed.
- This window technique is not supported by Esper => We implemented a “workaround” exploiting functionality of externally timed windows .



Stream Synchronization

- The QRS detection algorithm over the ECG stream introduces a variable delay ***Δt.***
- Introduce the same delay to the accelerometer stream.
- Accelerometer stream is sent through a FIFO queue with dynamic size.
- QRS detection function sets the dynamic size of the FIFO queue (also triggers the flushing of the aggregate window, in order to obtain dynamic windows).

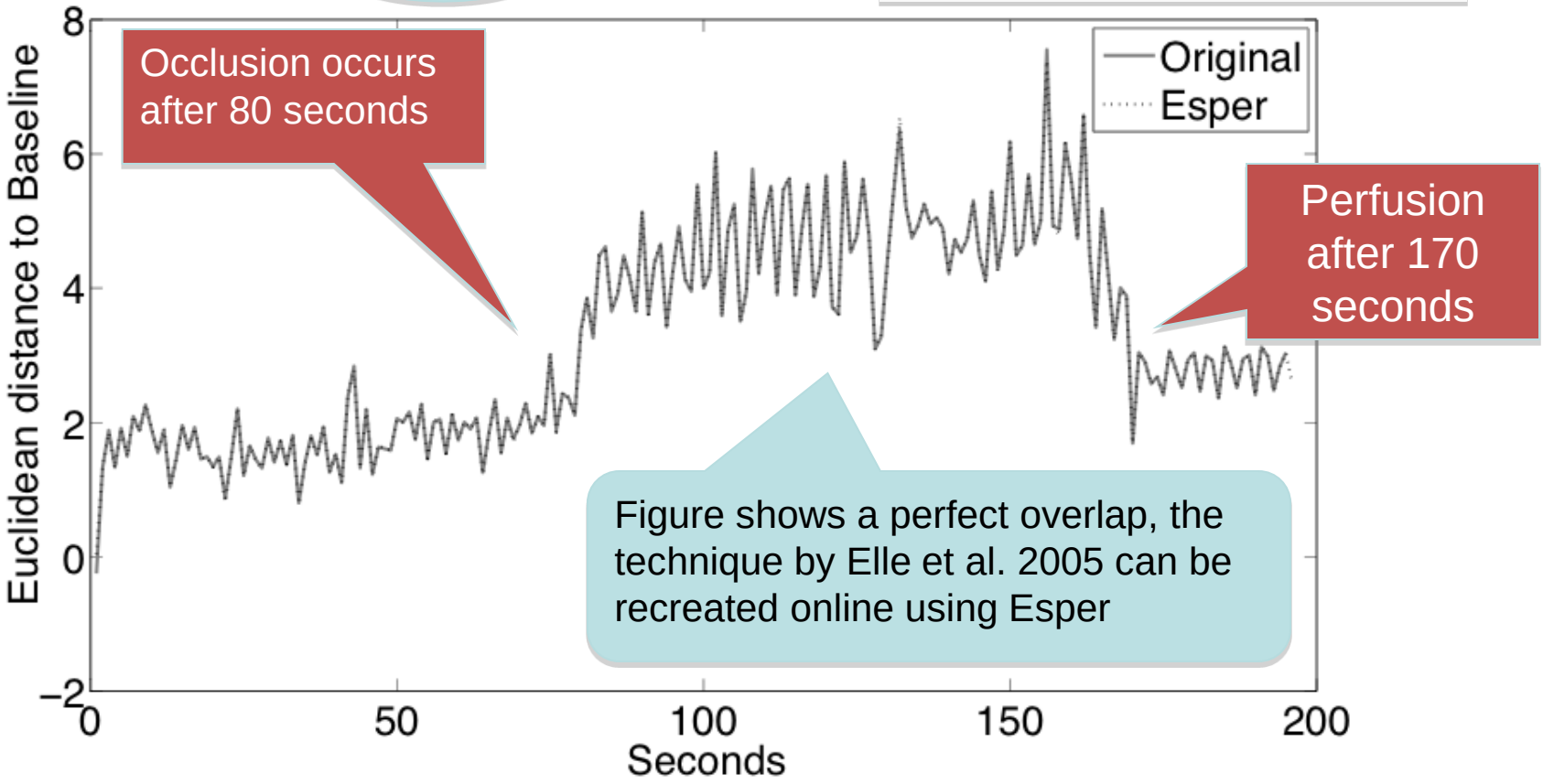




Results #1 (data set 1)

Easier than MATLAB

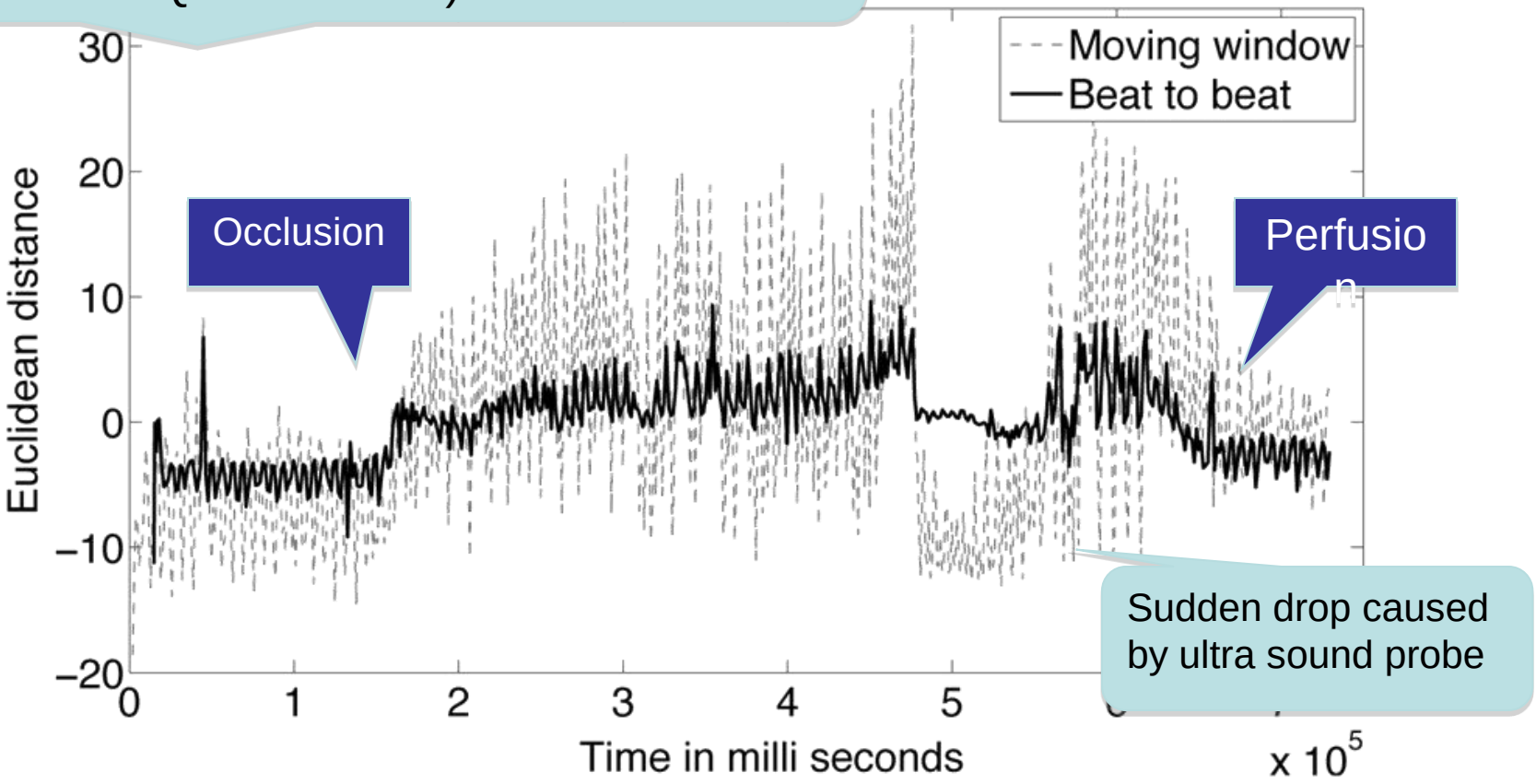
```
SELECT edv(y)
FROM Accelerometer
WINDOW LENGTH(512)
```



Results #2 (data set 2)

Plot shows fixed sliding window (512 samples) and dynamic triggered window (based on QRS detection) => less variance!

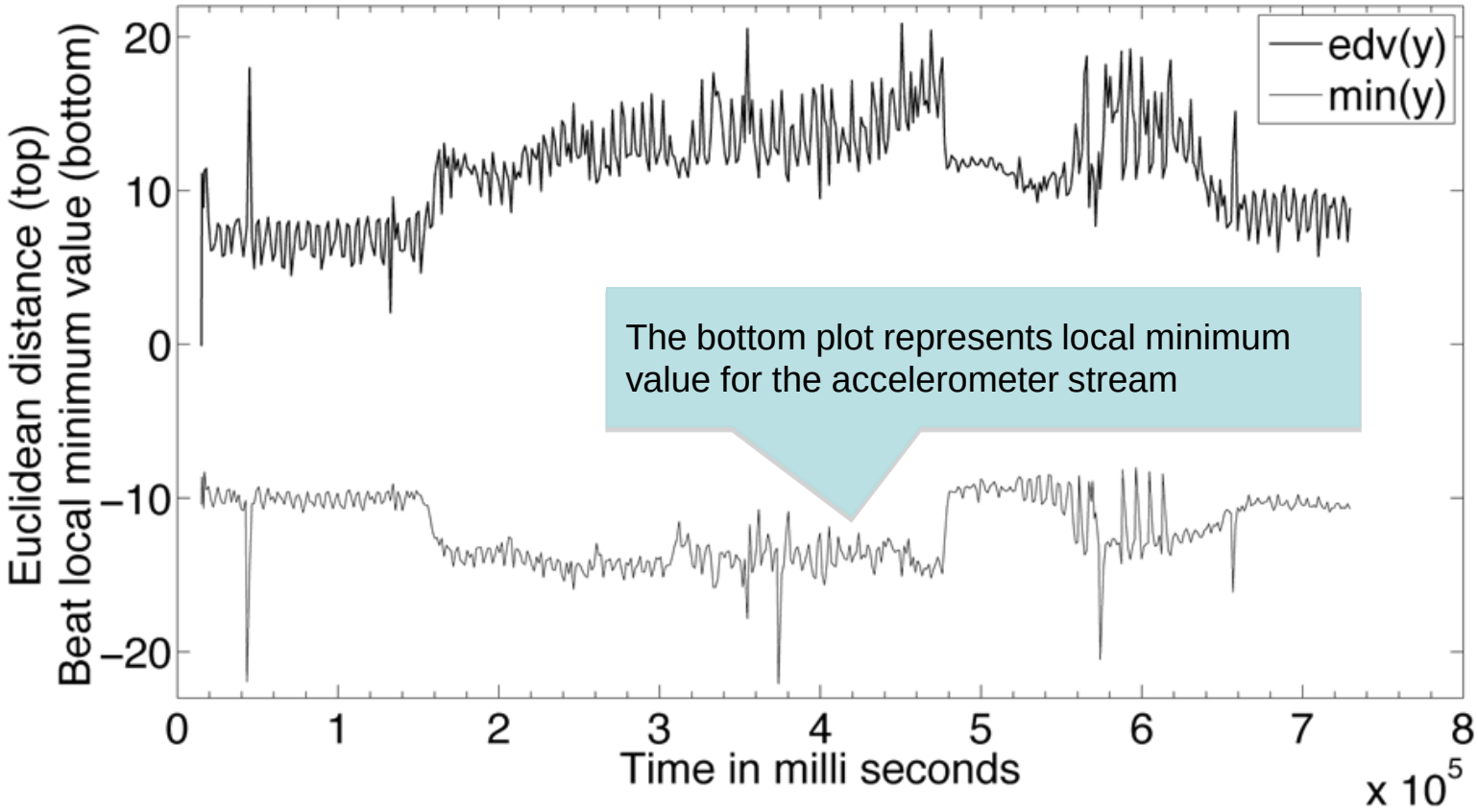
```
SELECT edv(y)
FROM Accelerometer TRIGGER
WINDOW BY QRSD(ECG.value)
```



Results #3 (data set 2)

Query with added local minimum value => easy to change!

SELECT edv(y), min(y) FROM Accelerometer TRIGGER WINDOW BY QRSD(ECG.value)



Implementation

- Java and Esper (open source component for event processing available at *http://esper.codehaus.org/)*
- Use existing window model, Esper is not changed
- Base window boundaries on the manipulated timestamps (registered as external timestamps in the Esper query)

  calculated from external / trigger query

Case study 1

- Ischemia detection (joint work with IVS, Oslo, Norway)
  - Real data from surgeries on pigs
  - **Accelerometer** attached to heart surface, used to identify irregular movements
  - **ECG** stream is used to detect each heartbeat (QRS Detection)
  - Upon detecting heartbeats, flush current window over the accelerometer stream

```
# Main query (Ischemia detection):
select edv(y), max(timestamp), max(realtime) from
Accelerometer.win:ext_timed(timestamp, 5 second)
```

```
# Trigger query (QRS detection):
select qrsdetect(value) from
ECG.win:length(1)
```

Case study 2

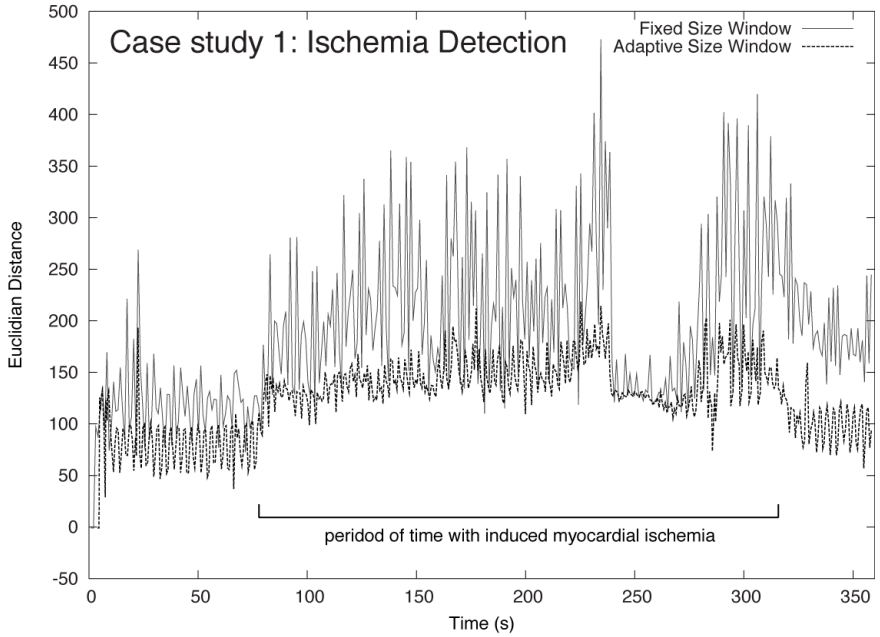
- Simple sine signal (we know ground truth)
  - Investigate more thoroughly the effect (overhead) of the window model itself

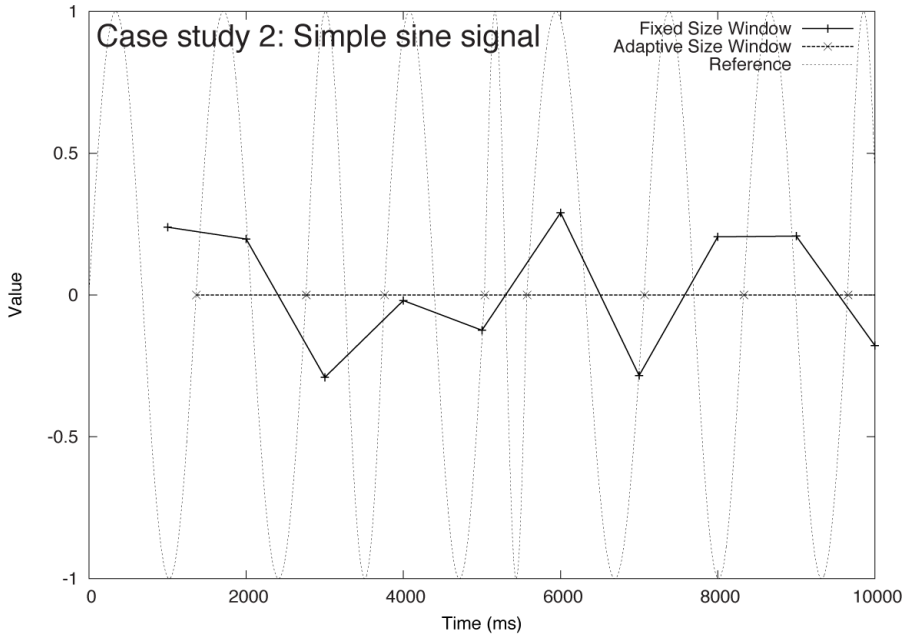
```
# Main query (Average value):
select avg(val), max(origin), max(fakeorigin) from
SineTriggerTuple.win:ext_timed(fakeorigin, 1 sec)
```

```
# Trigger query (Sine phase detection):
select max(origin), sinephasedetect(val) from
SineTriggerTuple.win:length(2)
```

Results

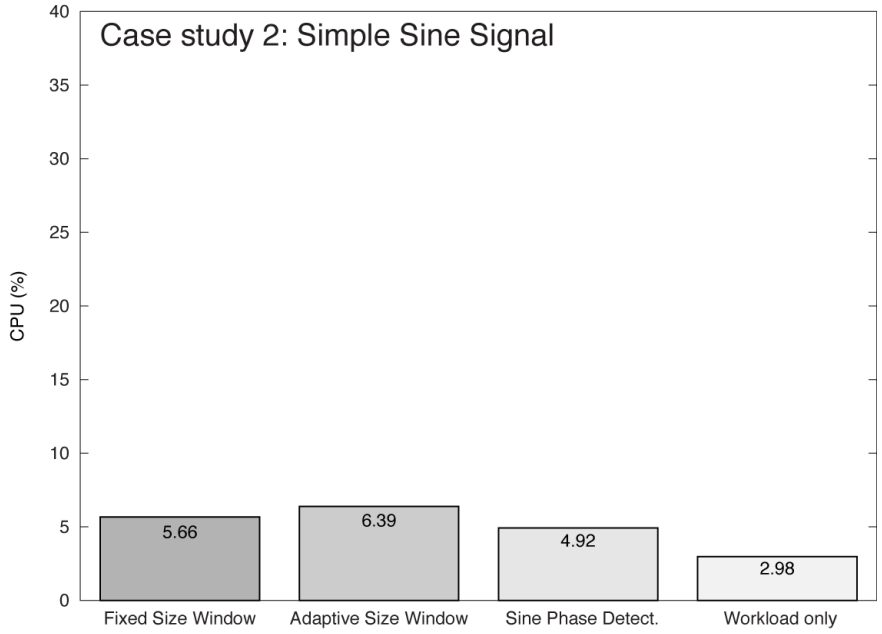
- Improvement of analysis results

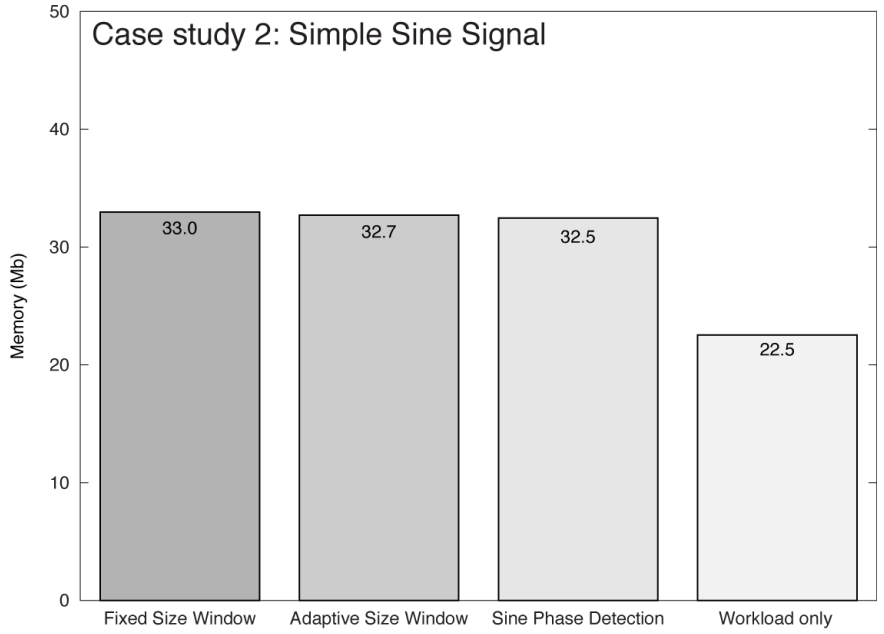




Results

- Low overhead for memory and CPU of the adaptive window technique confirmed by performance evaluation





Conclusion

- DSMSs can be used for real-time analysis => easy for medical practitioners to investigate novel methods
- Illustrated a method of online analysis of medical sensor data focusing on detection of myocardial ischemia
- Added beat-to-beat detection by using ECG
  - Results with less variance
- Introduced a new type of window for DSMSs: *Variable length triggered tumbling windows*