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Flexible Event pRocessing for big dAta aRchItectures

Distributed Data Streams and the Power of Geometry

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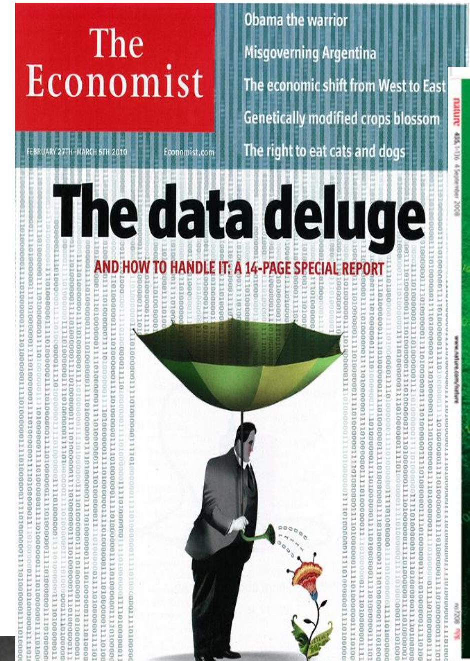
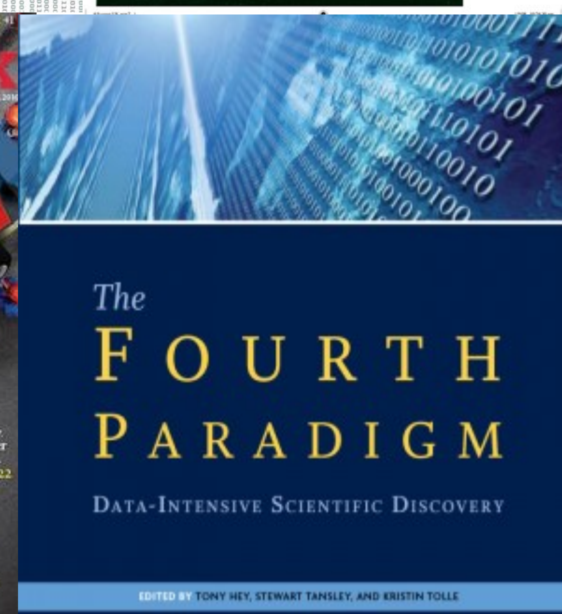
SEVENTH FRAMEWORK PROGRAMME

Big Data is Big News (and Big Business…)

- Mobile computing, sensornets, social networks, …
- Data-driven science
- How can we cost-effectively manage and analyze all this data…?





Big Data Challenges: The Four V's – and one D

- Volume: Scaling from Terabytes to Exa/Zettabytes
- Velocity: Processing massive amounts of *streaming data*
- Variety: Managing the complexity of multiple relational and non-relational data types and schemas
- Veracity: Handling inherent uncertainty and noise in the data
- Distribution: Dealing with massively distributed information
- *Our focus: Volume, Velocity, Distribution*

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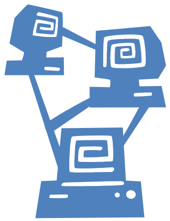
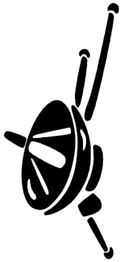
Velocity: *Continuous Stream Querying*

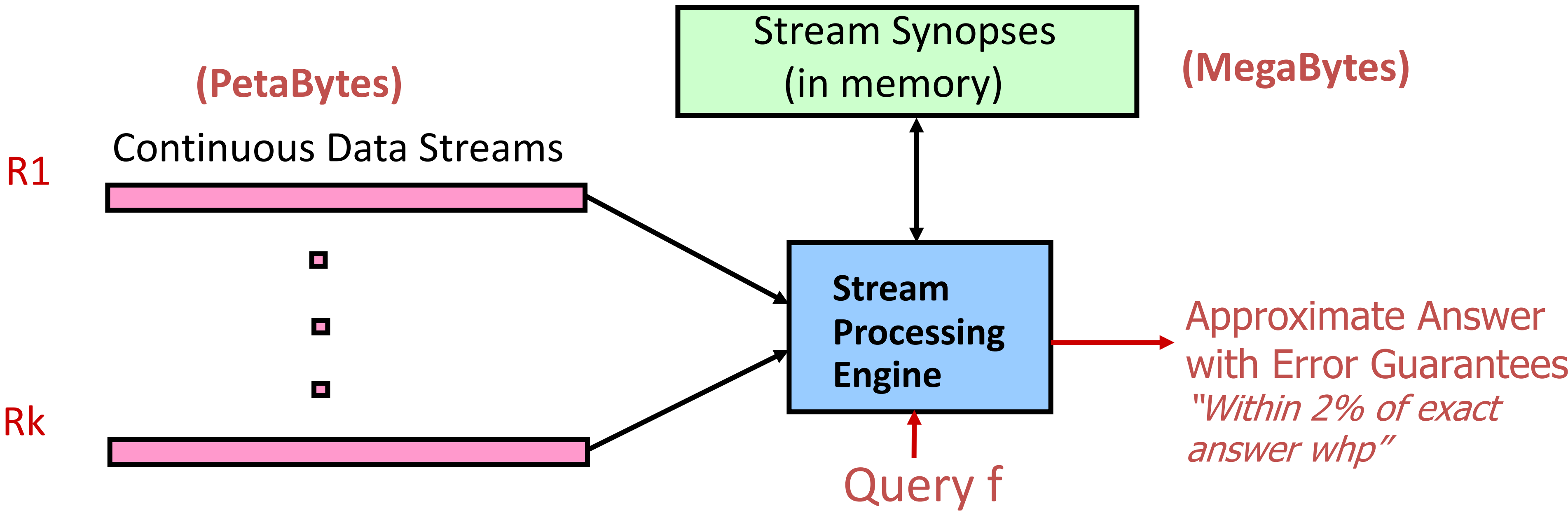
There are many scenarios where we need to monitor/ track events over streaming data:

- Network health monitoring within a large ISP
- Collecting and monitoring environmental data with sensors
- Observing usage and abuse of large-scale data centers





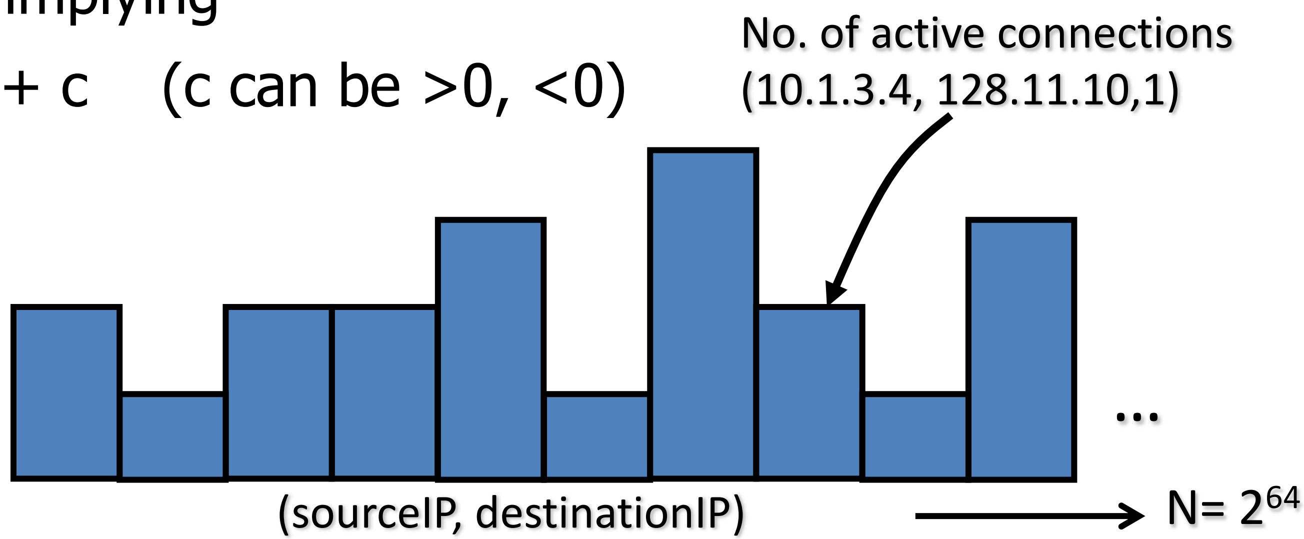
Stream Processing Model



- Approximate answers often suffice, e.g., trends, anomalies
- Stream synopses: *single-pass, small-space, small-time,* …

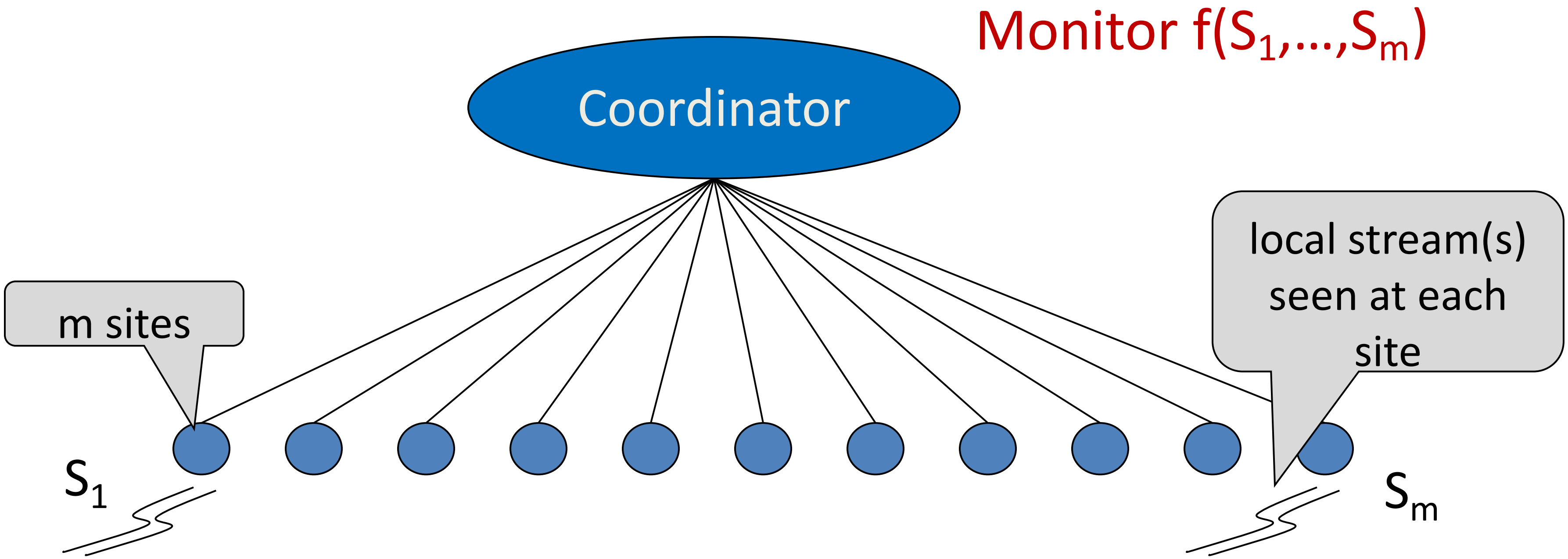
Model of a Relational Stream

- Relation "signal": *Large* array $v_S[1\ldots N]$ with values $v_S[i]$ initially zero
  - Frequency-distribution array of **S**
  - Multi-dimensional arrays as well (e.g., row-major)
- Relation implicitly rendered via a *stream of updates*
  - Update <x, c> implying
    - $v_S[x] := v_S[x] + c$ (c can be >0, <0)



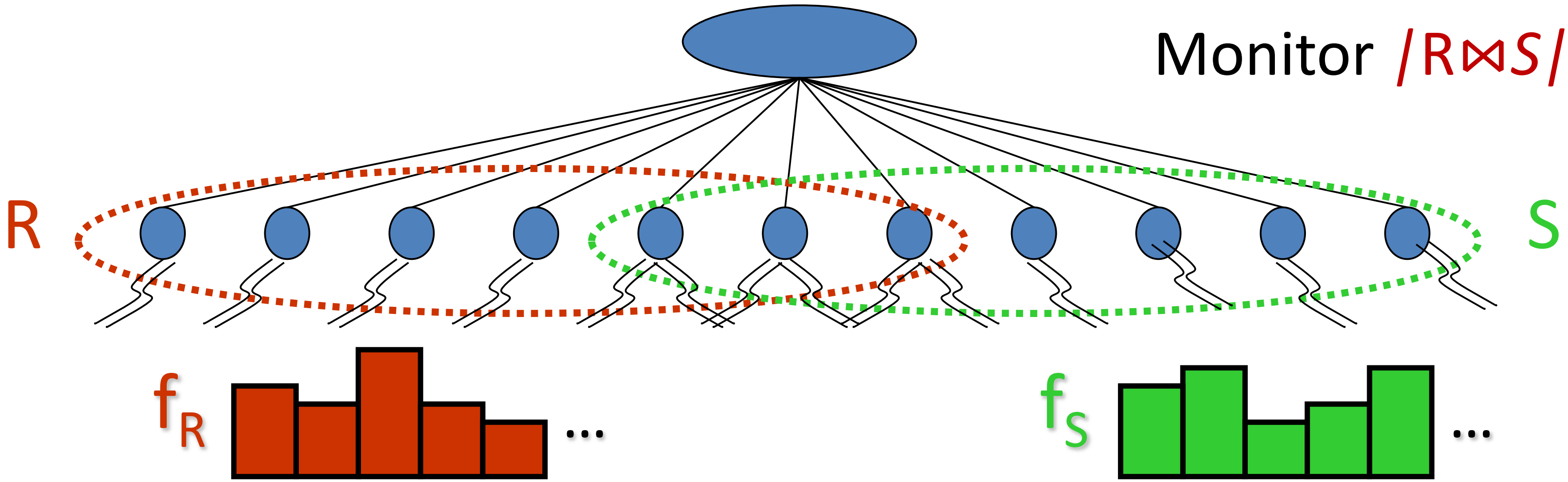
- *Goal:* Compute queries (functions) on such dynamic vectors in "small" space and time (<< N)

Velocity & Distribution: *Continuous Distributed Streaming*



- Other structures possible (e.g., hierarchical, P2P)
- Goal: *Continuously track* (global) query over streams at coordinator
  - Using small space, time, and ***communication***
  - Example queries:
    - Join aggregates, Variance, Entropy, Information Gain, …

Tracking Complex Aggregate Queries



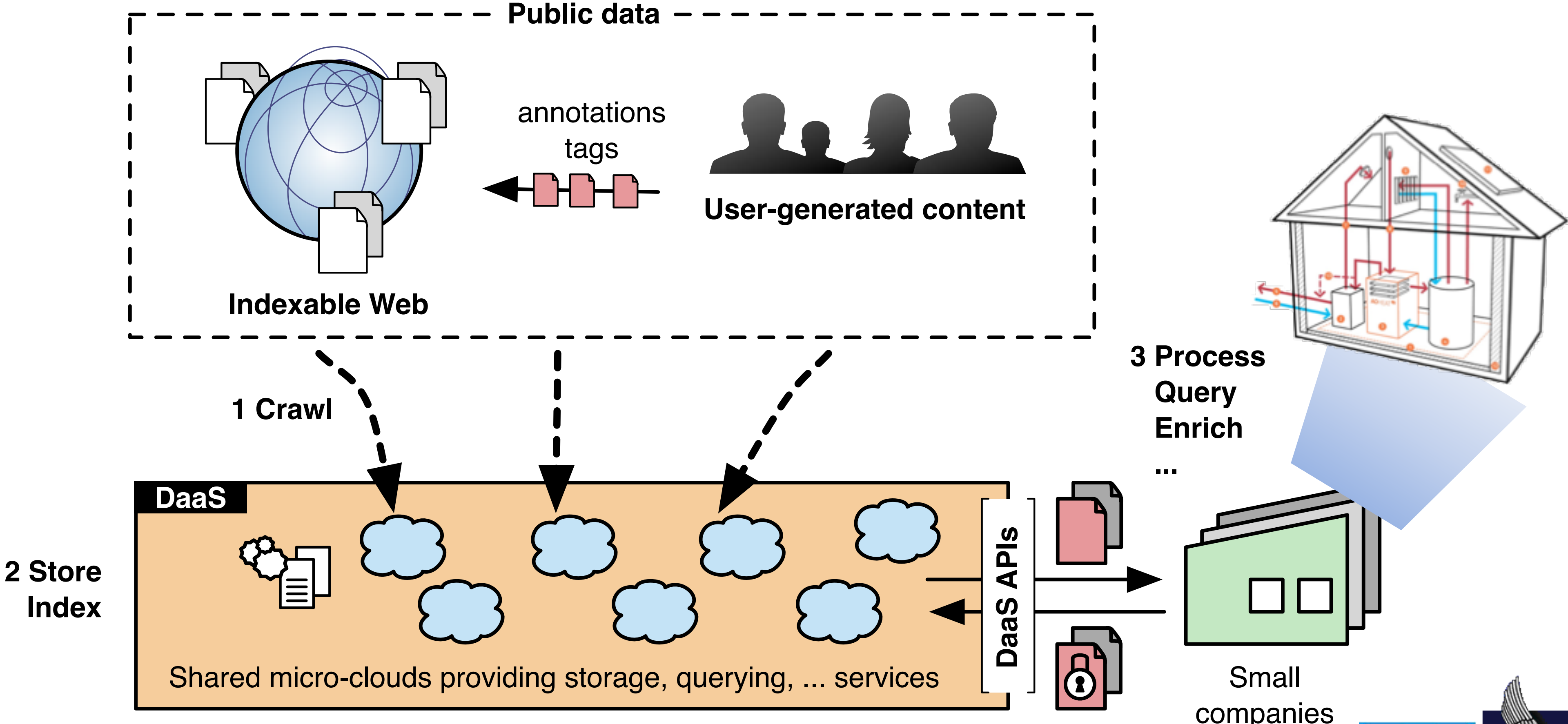
- *Class of queries:* Generalized inner products of streams

  $|R \bowtie S| = f_R \cdot f_S = \sum_v f_R[v] \, f_S[v]$

  - Join/multi-join aggregates, range queries, heavy hitters, histograms, wavelets, …

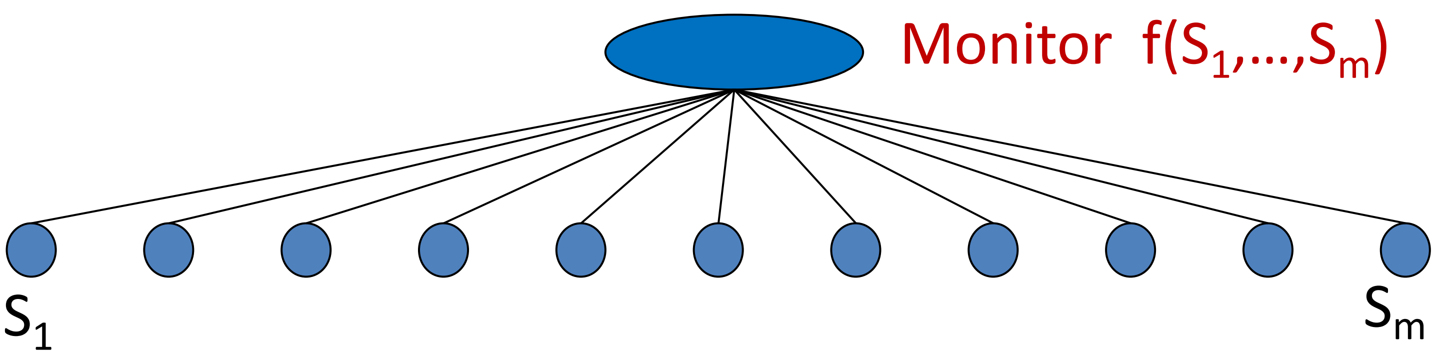
Example: LEADS Elastic μClouds Architecture

(http://leads-project.eu)



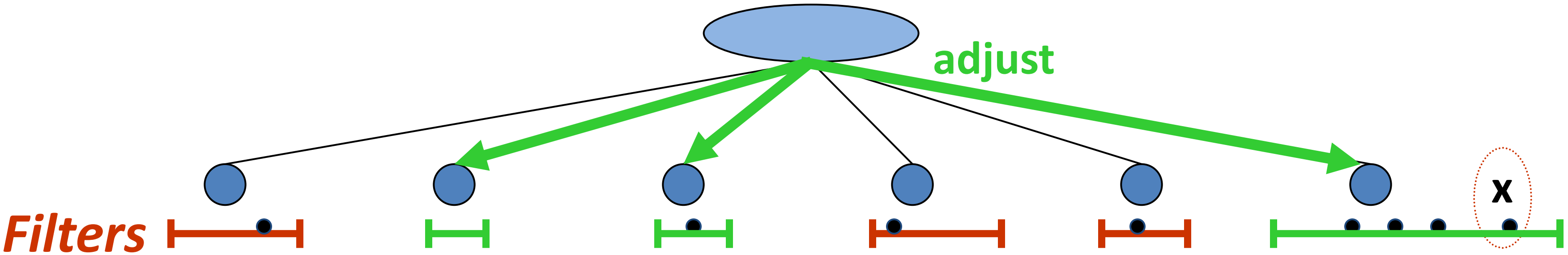
Continuous Distributed Streaming

- But… local site streams continuously change! New readings/data…
- Classes of monitoring problems
  - **Threshold Crossing**: Identify when $f(S)>\tau$
  - **Approximate Tracking**: $f(S)$ within **guaranteed accuracy bound θ**
    - Tradeoff *accuracy and communication / processing cost*
- Naïve solutions must *continuously* centralize all data
  - Enormous communication overhead!
- Instead, *in-situ* stream processing using *local constraints* !



Communication-Efficient Monitoring

- **Key Idea:** *"Push-based" in-situ processing*
  - *Local filters* installed at sites process local streaming updates
    - Offer bounds on local-stream behavior (at coordinator)
  - *"Push"* information to coordinator only when filter is violated
  - ***"Safe"!*** Coordinator sets/adjusts local filters to guarantee accuracy



  - Easy for linear functions! Exploit additivity…
  - ***Non-linear f() …??***

Outline

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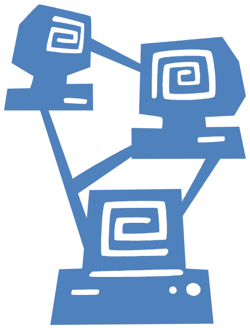
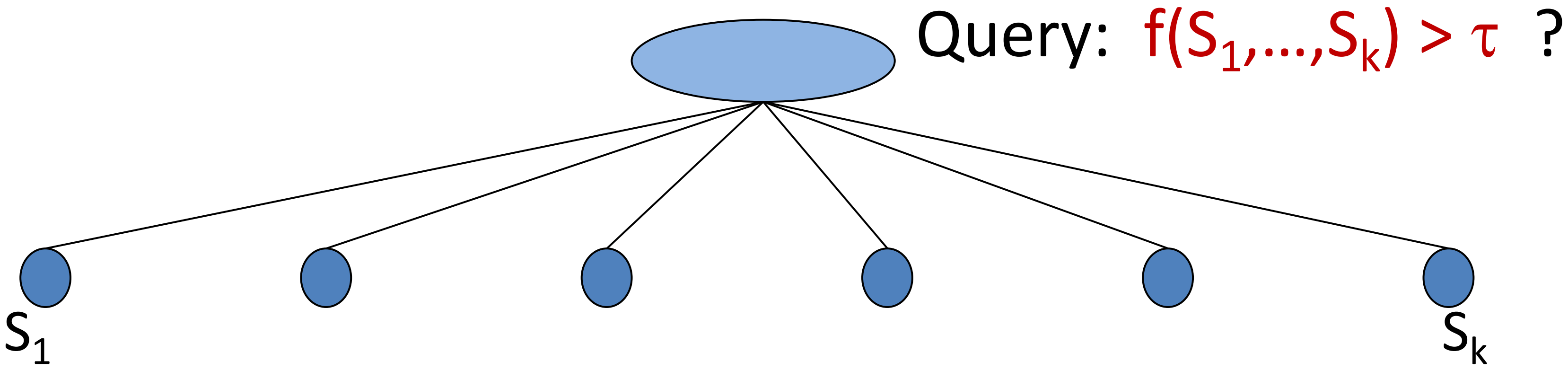
- The Geometric Method (GM)
- GM + Sketches, GM + Prediction Models
- Towards Convex Safe Zones (SZs)
- Future Directions & Conclusions



Monitoring General, Non-linear Functions



- For general, non-linear $f()$, problem is a lot harder!
  - E.g., information gain over global data distribution
- Non-trivial to decompose the global threshold into "safe" local site constraints
    - E.g., consider $N=(N_1+N_2)/2$ and $f(N) = 6N - N^2 > 1$
      Tricky to break into thresholds for $f(N_1)$ and $f(N_2)$

The Geometric Method

- A general purpose geometric approach [SIGMOD'06]
  - Monitor **function domain** rather than the range of values!

- Each site tracks a local statistics *vector* v_i (e.g., data distribution)

- Global condition is $f(v) > \tau$, where $v = \sum_i \lambda_i v_i \quad (\sum_i \lambda_i = 1)$
  - E.g., v = *average* of local statistics vectors

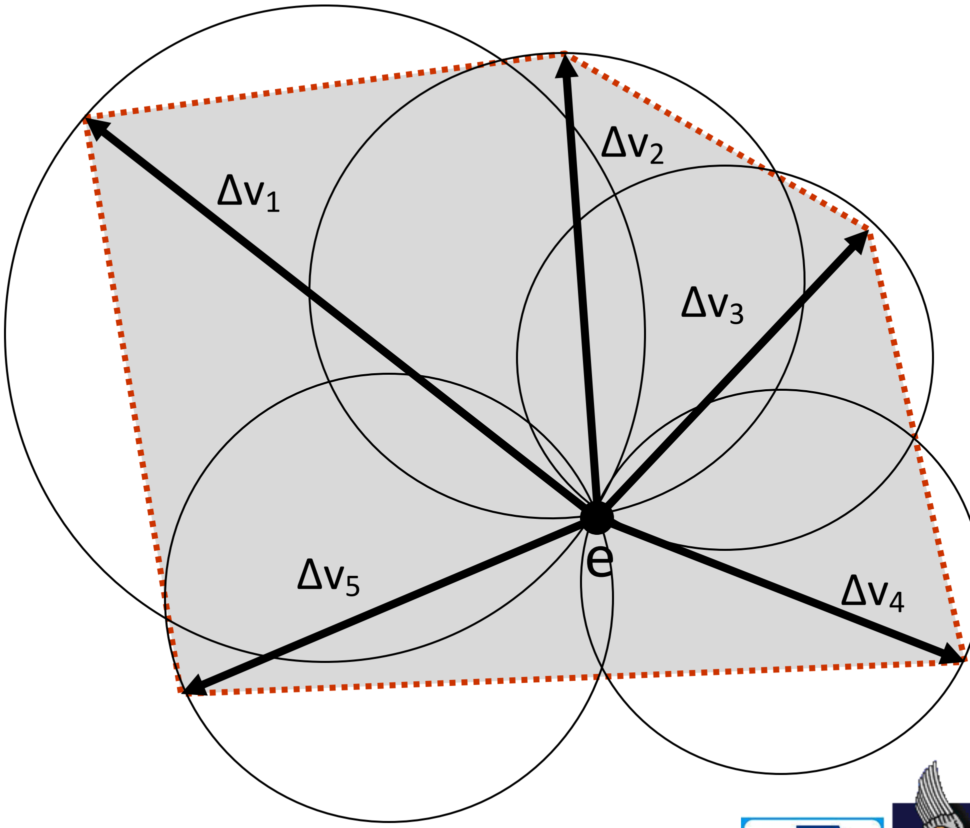
- All sites share estimate $e = \sum_i \lambda_i v_i'$ of v
  based on latest update v_i' from site i

- Each site i tracks its drift from its most recent update $\Delta v_i = v_i - v_i'$

Covering the Convex Hull

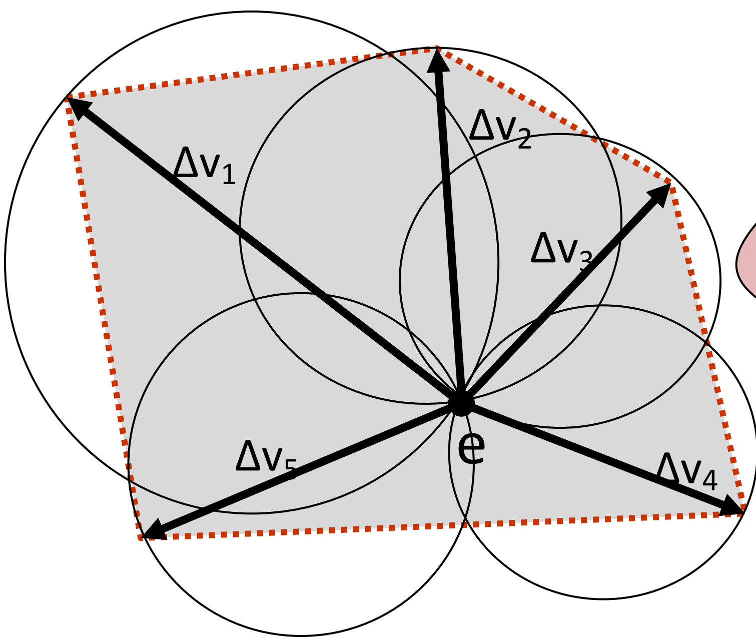
- Key observation: $v = \sum_i \lambda_i \cdot (e+\Delta v_i)$
  (a convex combination of "translated" local drifts)

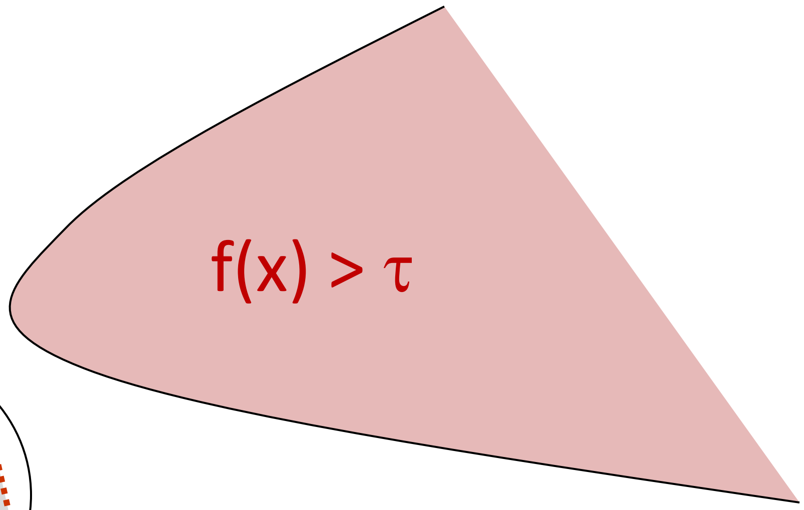
- v lies in the convex hull of the $(e+\Delta v_i)$ vectors
- Convex hull is completely covered by spheres with radii $||\Delta v_i/2||_2$ centered at $e+\Delta v_i/2$
- Each such sphere can be constructed independently



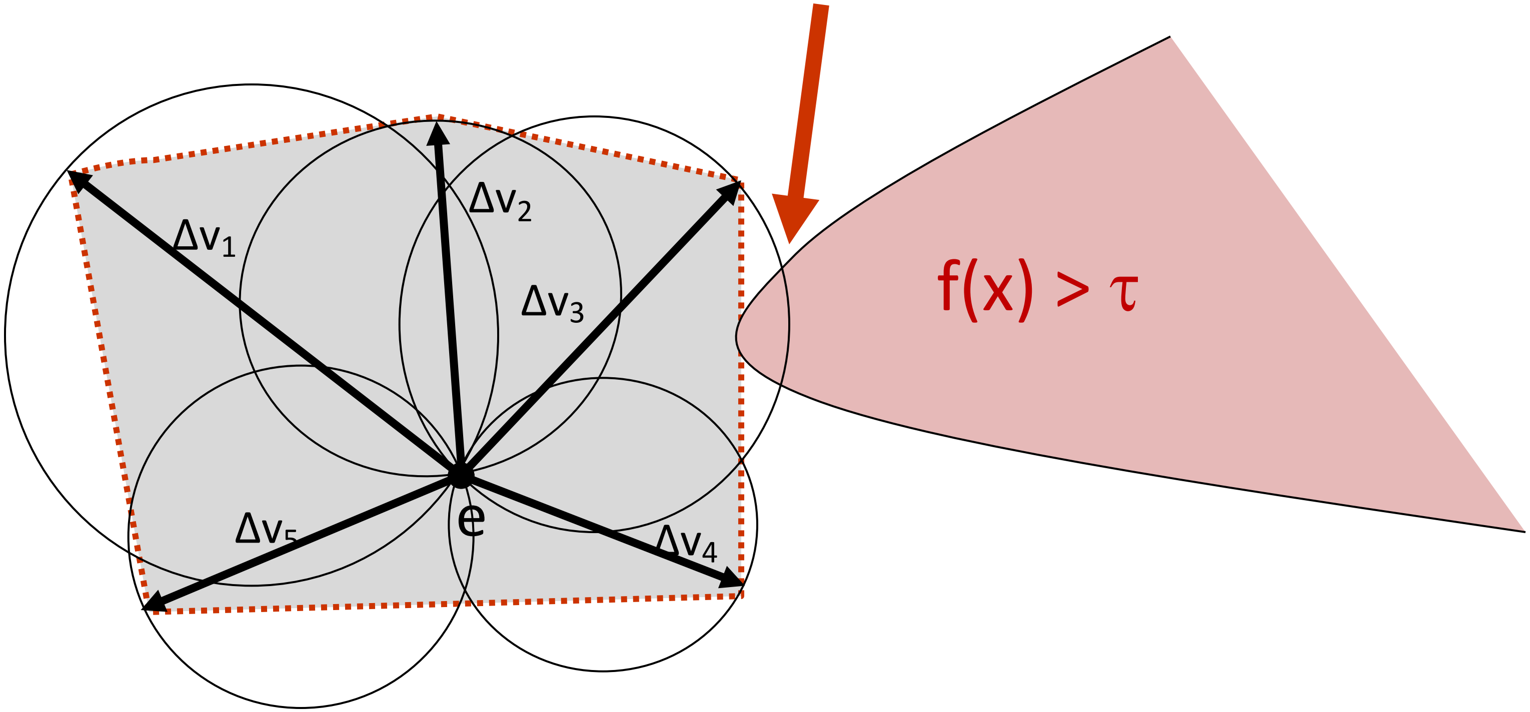
Monochromatic Regions

- Monochromatic Region: For all points x in the region $f(x)$ is on the same side of the threshold ($f(x) > \tau$ or $f(x) \leq \tau$)
- Each site independently checks its sphere is monochromatic
  - Find max and min for f() in local sphere region (may be costly)
  - Send updated value of v_i if not monochrome



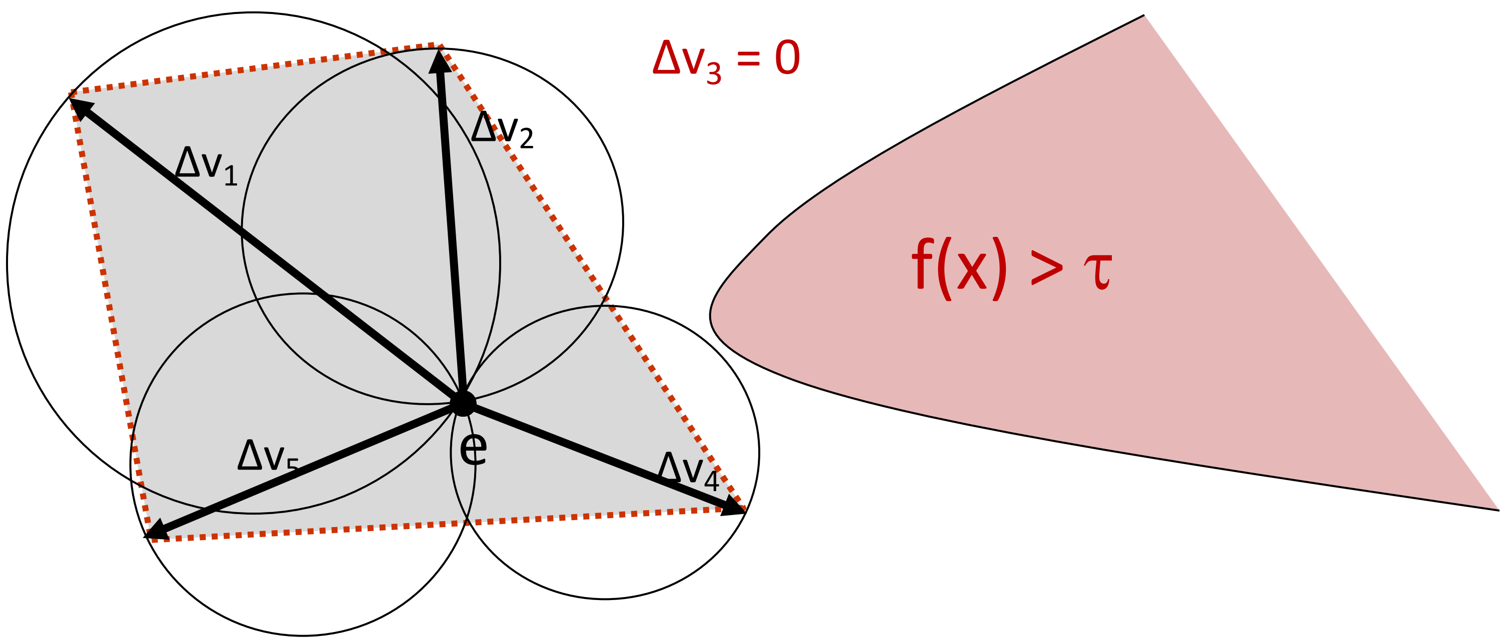


Restoring Monochromicity



Restoring Monochromicity

- After update, $||\Delta v_i||_2 = 0 \Rightarrow$ Sphere at i is monochromatic
  - Global estimate e is updated, may cause more site updates
- Coordinator case: Can allocate local slack vectors to sites for "localized" resolutions



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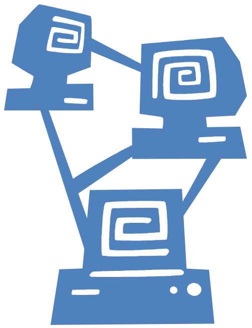
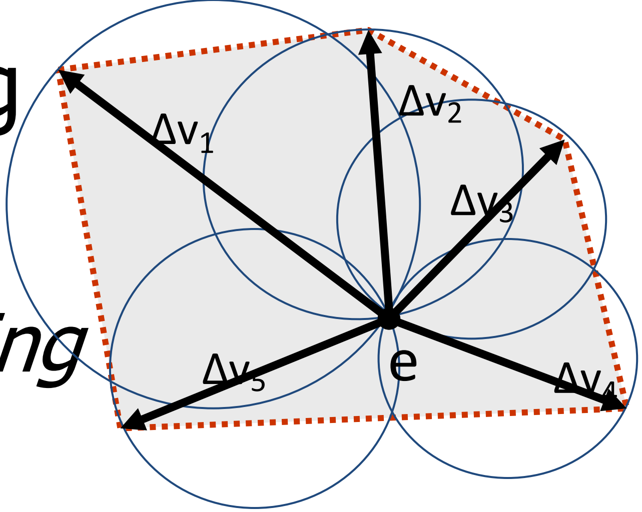


Geometric Query Tracking using AMS Sketches [VLDB'13]



- *Continuous approximate monitoring*
  - Track value of a function to within specified accuracy bound θ

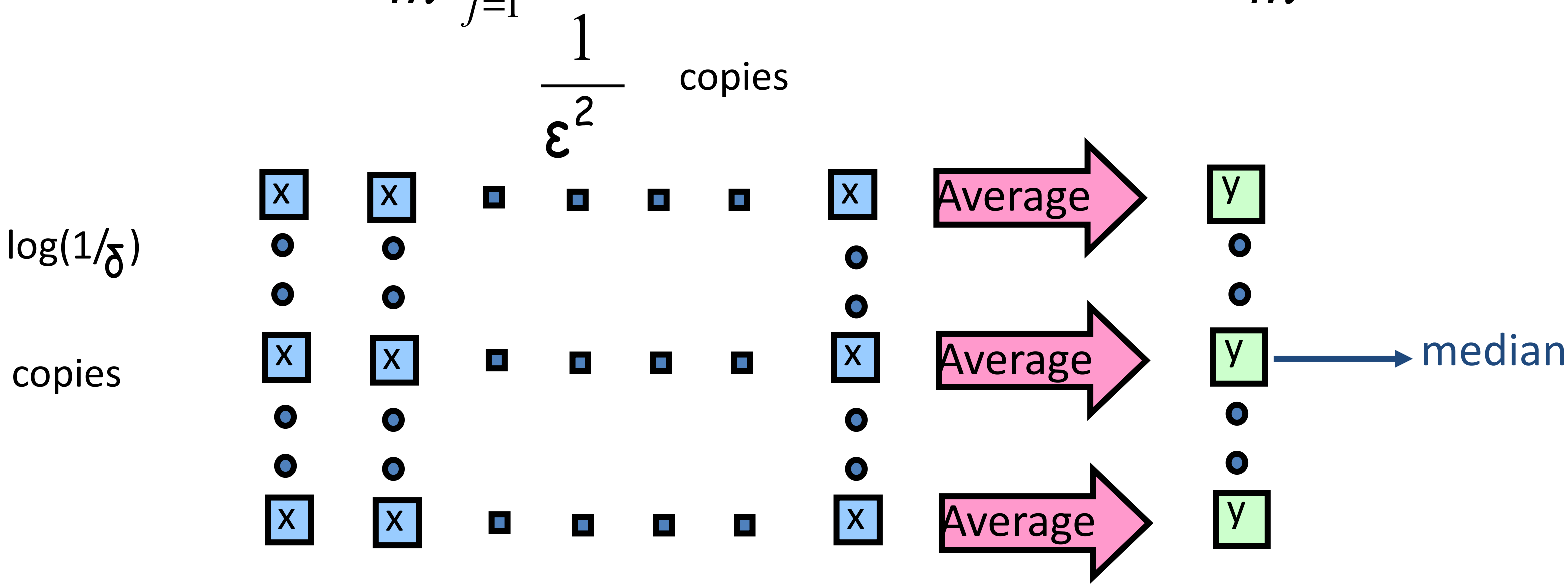
- Too much local info ➔ *Local AMS sketch summaries*
  - Bounding regions for the *lower-dimensional sketching space*
  - Account for sketching error ε

- *Key Problems: (1) Minimize data exchange volume (2) Deal with highly-nonlinear AMS estimator*

Monitored Function…?

AMS Estimator function for Self-Join

$$f(sk(v)) = median_{i=1..n}\{\frac{1}{m}\sum_{j=1}^{m} sk(v)[i,j]^2\} = median_{i=1..n}\{\frac{1}{m}\| sk(v)[i] \|^2\}$$



- Theorem(AMS96): Sketching approximates $\| v \|_2^2$ to within an error of $\pm\varepsilon\|v\|_2^2$ with probability $\geq 1-\delta$ using $O(\frac{1}{\varepsilon^2}\log(1/\delta))$ counters

Geometric Query Monitoring using AMS Sketches [VLDB'13]

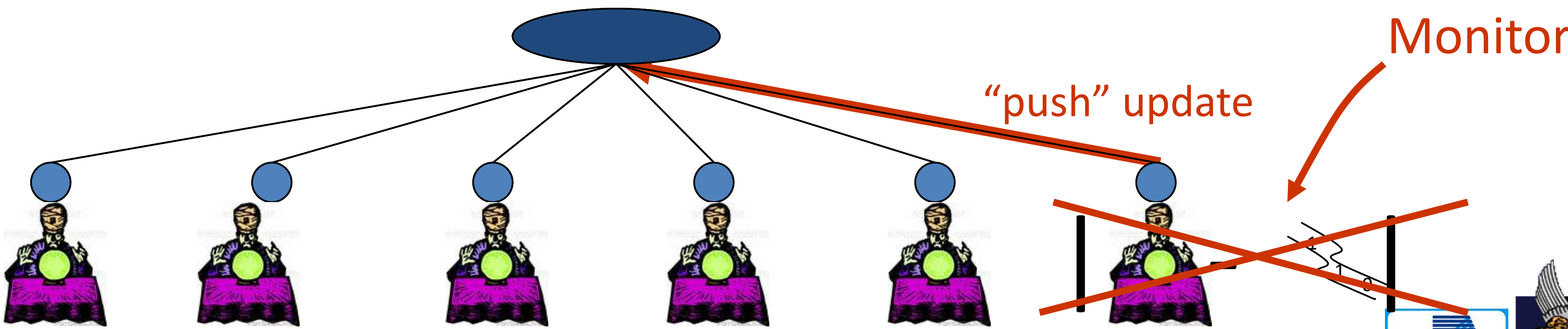
- Efficiently deciding ball monochromicity for median
  - Fast greedy algorithm for determining the distance to the inadmissible region

- *(Non-trivial!)* extension to *general join aggregates*

- Minimizing volume of data exchanges
  - Sketches can still get pretty large!
  - Can reduce to monitoring in O(log(1/δ)) dimensions

Exploiting Shared Prediction Models

- Naïve *"static"* prediction: Local stream assumed "unchanged" since last update
  - No update from site ⇒ last update ("predicted" value) is unchanged ⇒ global estimate vector unchanged
- *Dynamic prediction models* of site behavior
  - Built locally at sites and *shared* with coordinator
  - Model complex stream patterns, reduce number of updates
  - But... more complex to maintain and communicate



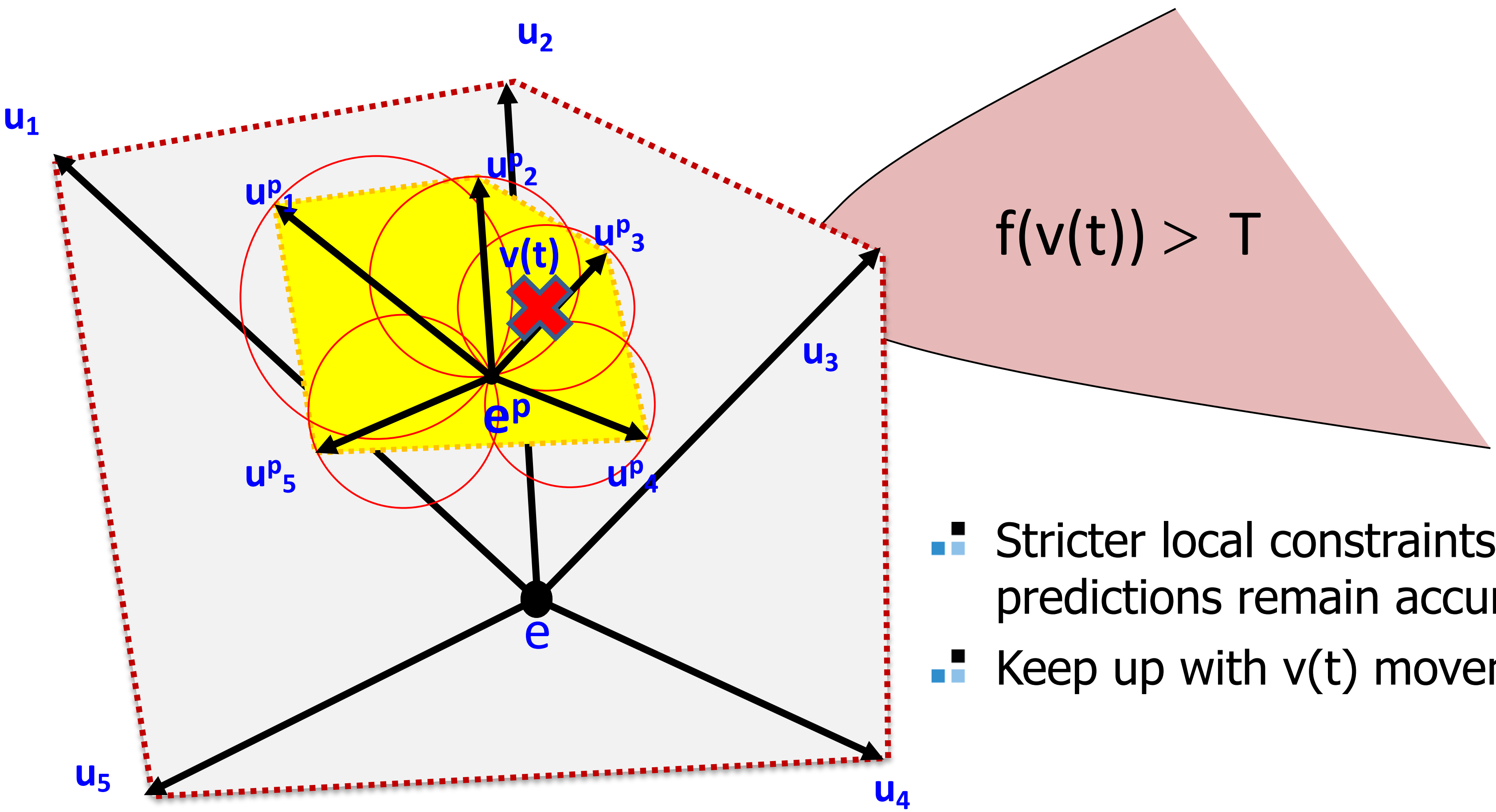
Adopting Local Prediction Models

[VLDB'05, TODS'08]

Model	Predicted v_i
Linear Growth	$v_i^p(t) = \frac{t}{t_s} v_i(t_s)$
Velocity/ Acceleration	$v_i^p(t) = v_i(t_s) + (t - t_s)vel_i + (t - t_s)^2 acc_i$
Static — Equivalent to the basic framework	$v_i^p(t) = v_i(t_s)$

Predicted Global Vector: $e^p(t) = \sum \lambda_i v_i^p(t)$

Prediction-based Geometric Monitoring
[SIGMOD'12, TODS'14]



- Stricter local constraints if local predictions remain accurate
- Keep up with v(t) movement

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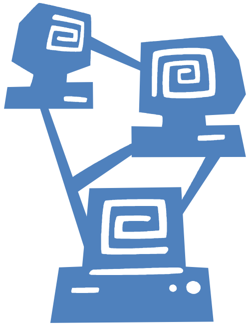
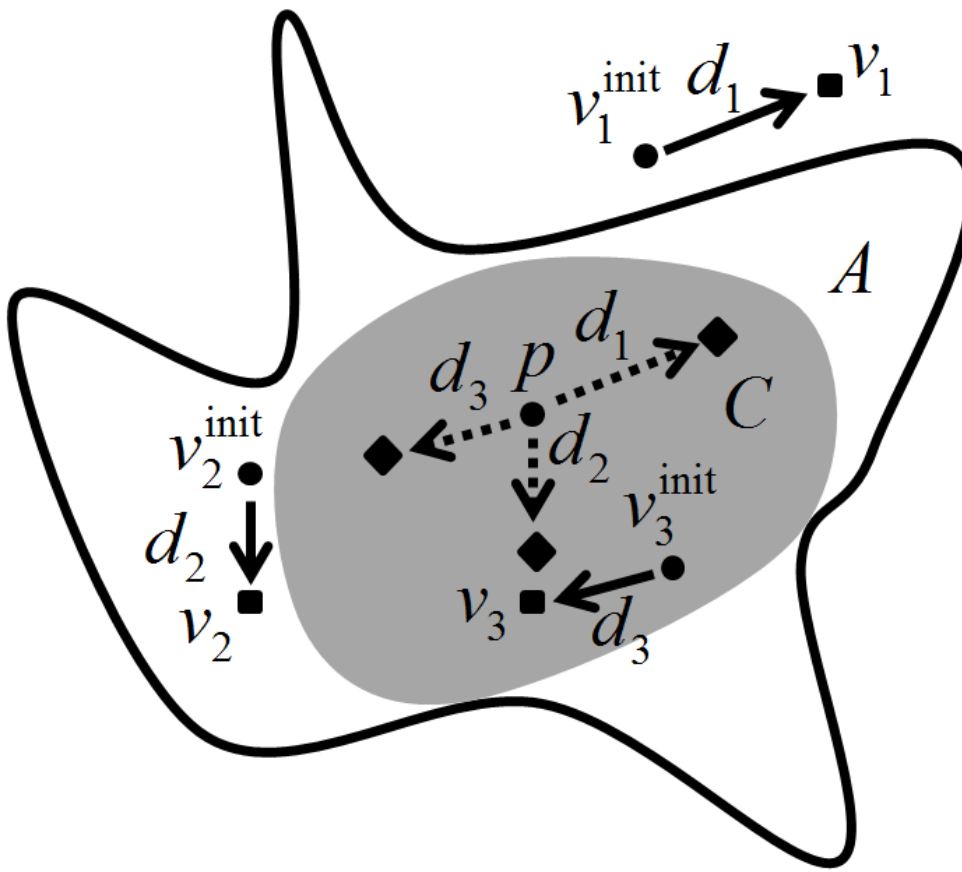


SEVENTH FRAMEWORK PROGRAMME

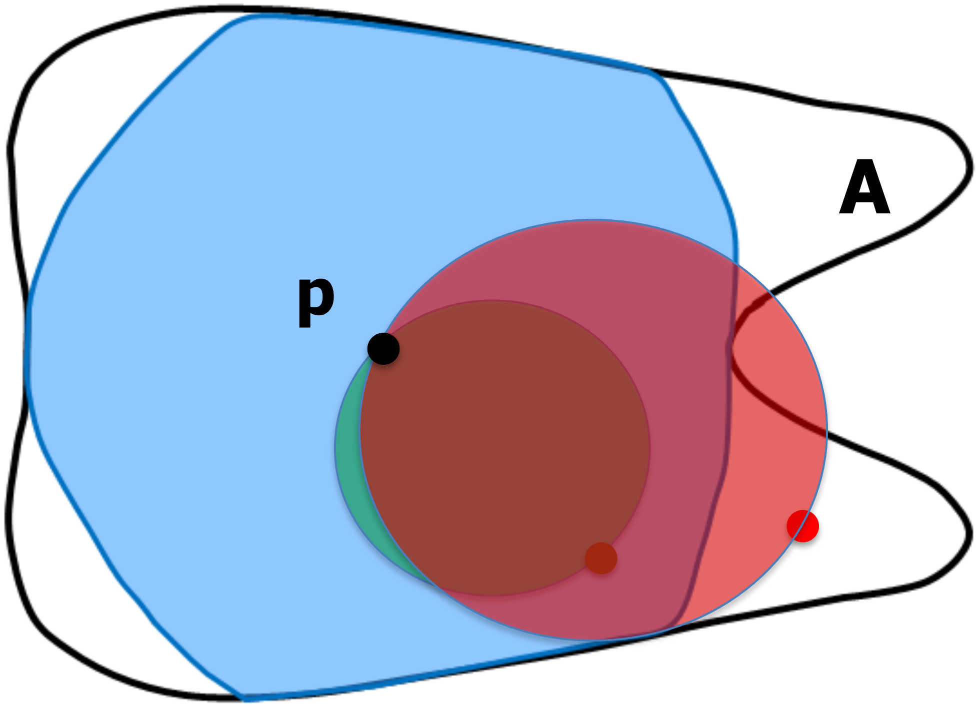
From Bounding Spheres to Safe Zones (SZs)

- **Safe Zone: Any convex subset of the Admissible Region**
  - As long as translated drifts stay within SZ, we are "safe"
    - By convexity

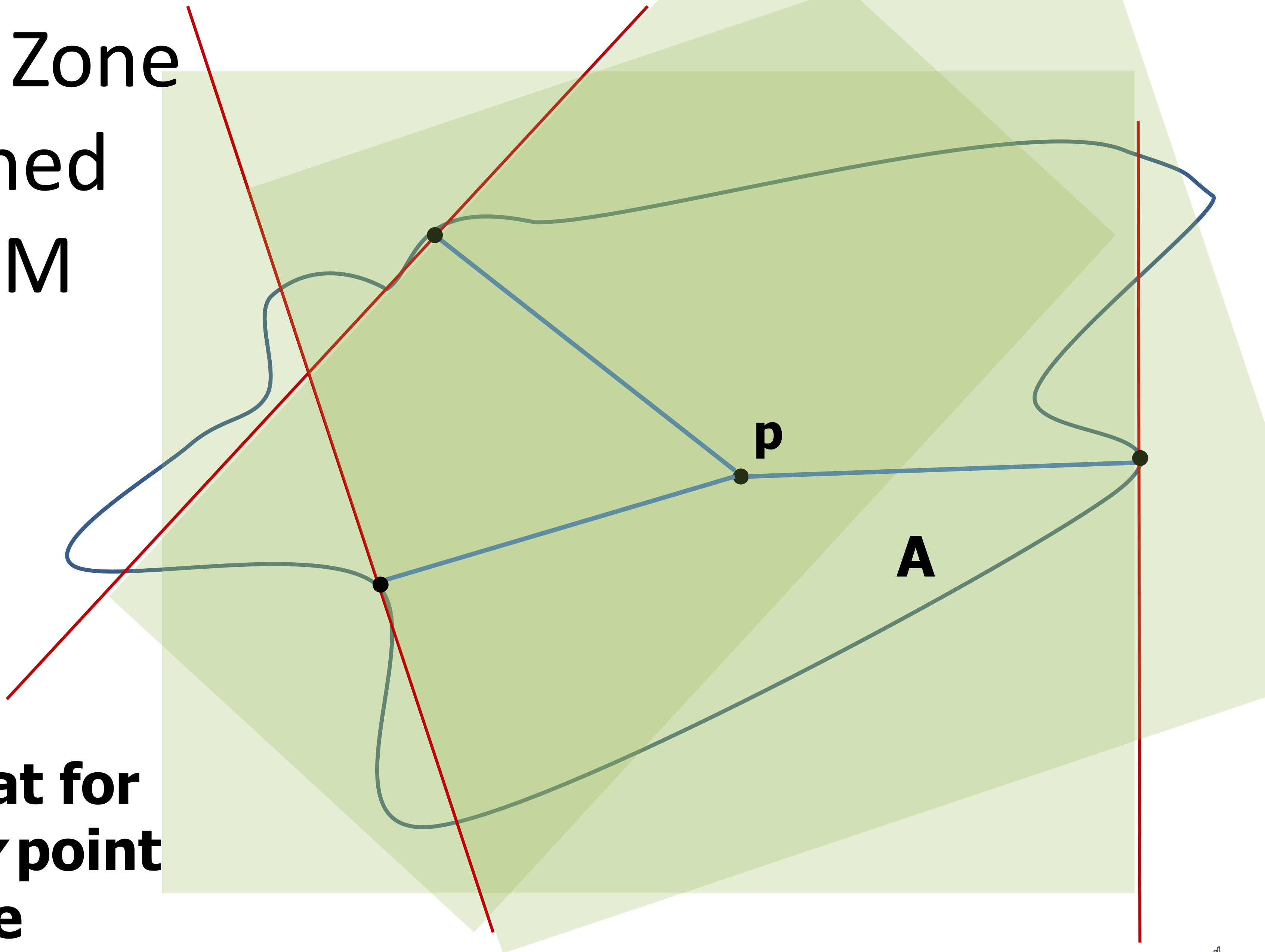
- Aim for large SZs, far from the boundary



Safe Zone defined by GM



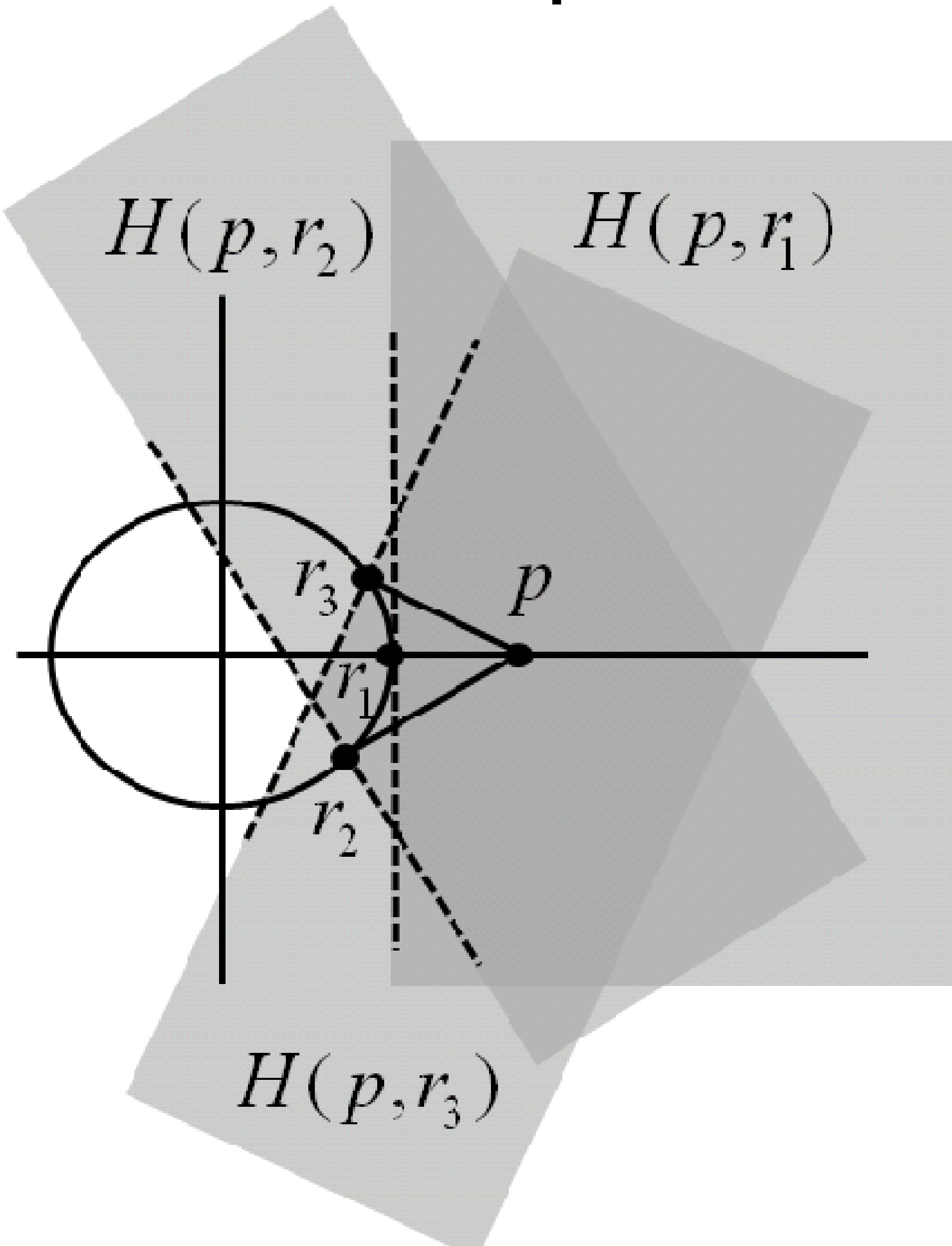
Safe Zone defined by GM



Repeat for *every* point on the boundary

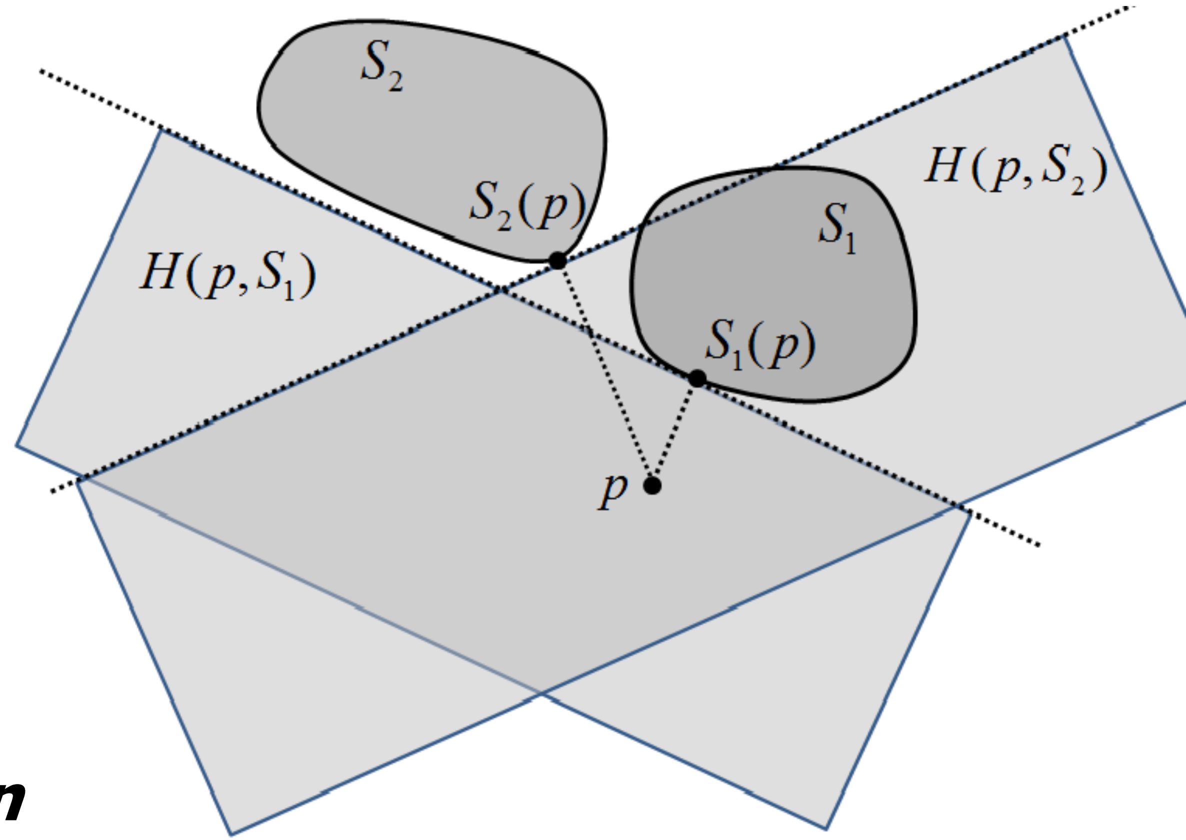
GM Safe Zones can be Far from Optimal!

- For instance, when inadmissible region is convex
- Taking the intersection of all half-spaces is overly restrictive
- In this case, half-space H(p,r1) is clearly the optimal SZ!



SZs through Convex Decompositions [VLDB’15]

- Inadmissible region is (can be covered by) a union of convex sets
- Just intersect half-spaces that separate p from each set
  - Avoid *redundancy!*



$$S_1(p), S_2(p): \text{"support vectors"}$$

- ***Provably better than GM!***
- Application in sketches and median monitoring

A “Cookbook” for Distributed Stream Monitoring?

- GM/bounding spheres is a generic, off-the-shelf technique
    - Any function, but can be far from optimal
- SZs: much better performance but must be designed for function/data at hand
    - Some initial progress on automated SZ construction (difficult optimization problem) **[TKDE’14]**
    - Work on generic mechanisms for composing SZs **[working paper]**

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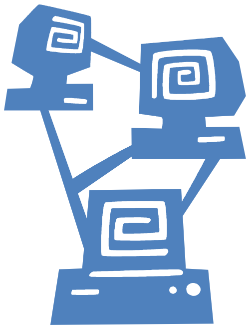


Work in CD Streaming

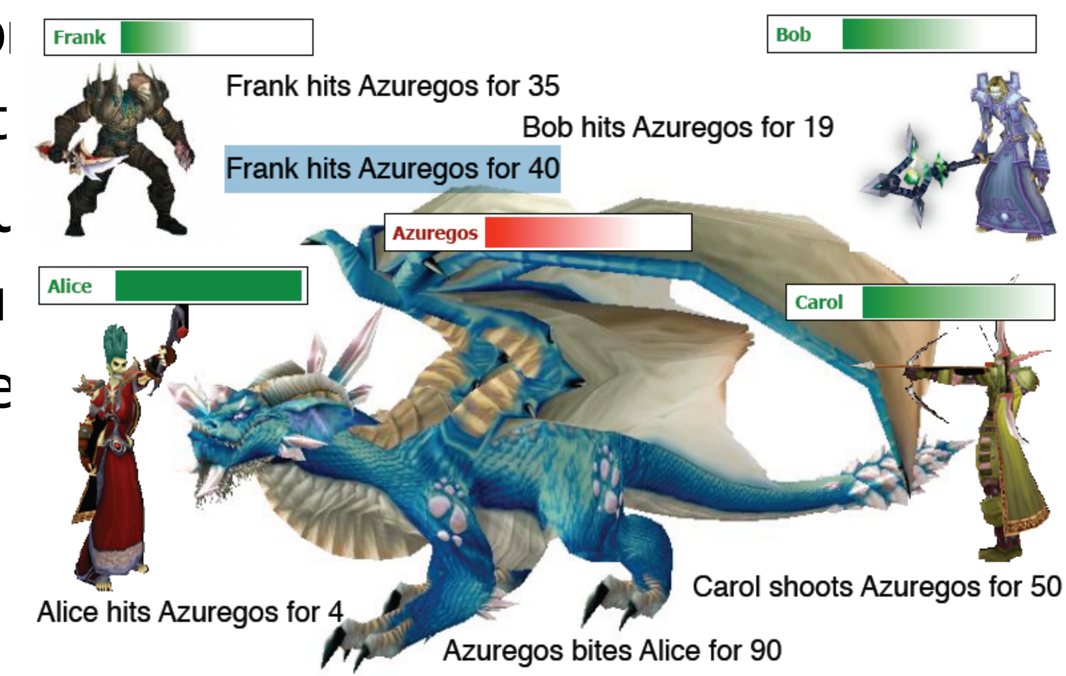
- Much interest in these problems in TCS and DB areas
- Many functions of (global) data distribution studied:
  - Set expressions [Das,Ganguly,G,Rastogi'04]
  - Quantiles and heavy hitters [Cormode,G, Muthukrishnan, Rastogi'05]
  - Number of distinct elements [Cormode et al.,'06]
  - Spectral properties of data matrix [Huang,G, et al.'06]
  - Anomaly detection in networks [Huang ,G, et al.'07]
  - Samples [Cormode et al.'10]
  - Counts, frequencies, ranks [Yi et al.,'12]
- NII Shonan meeting on Large-Scale Distributed Computation

  http://www.nii.ac.jp/shonan/seminar011/

SEVENTH FRAMEWORK PROGRAMME

Monitoring Systems

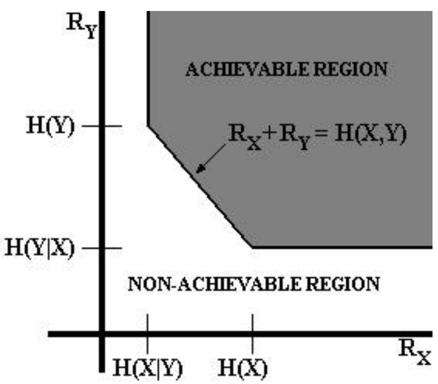
- Much theory developed, but less progress on deployment
- Some empirical study in the lab, with recorded data
- Still, applications abound: Online Games [Heffner, Malecha'09]
  - Need to monitor many varying stats and bound communication
  - Also, Distributed CEP systems (FERARI project)
- Several steps to follow:
  - Build lib … ms
  - Evolve t … outed DBMSs?)
- Several qu
  - What fu … specific?
  - What ke … onitoring?

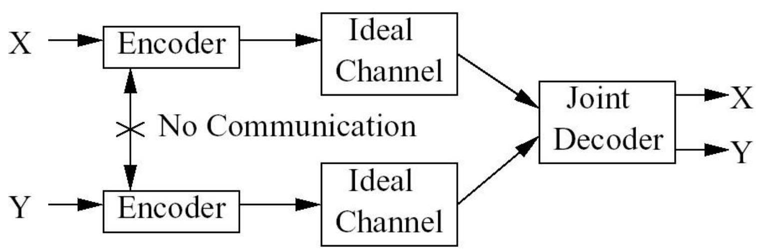


Theoretical Foundations

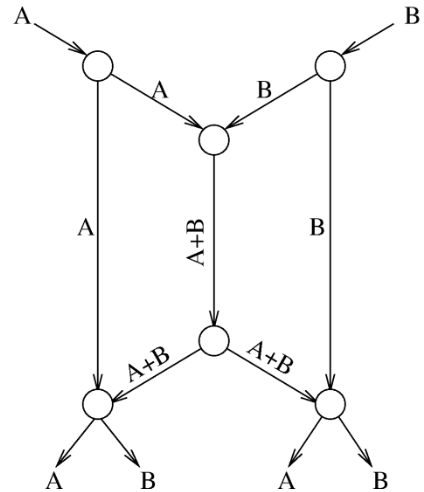
"Communication complexity" studies lower bounds of distributed one-shot computations

- Lower bounds for various problems, e.g., **count distinct** (via reduction to abstract problems)
- Need new theory for continuous computations
  - Link to distributed source coding or network coding?





Slepian-Wolf theorem [Slepian Wolf 1973]

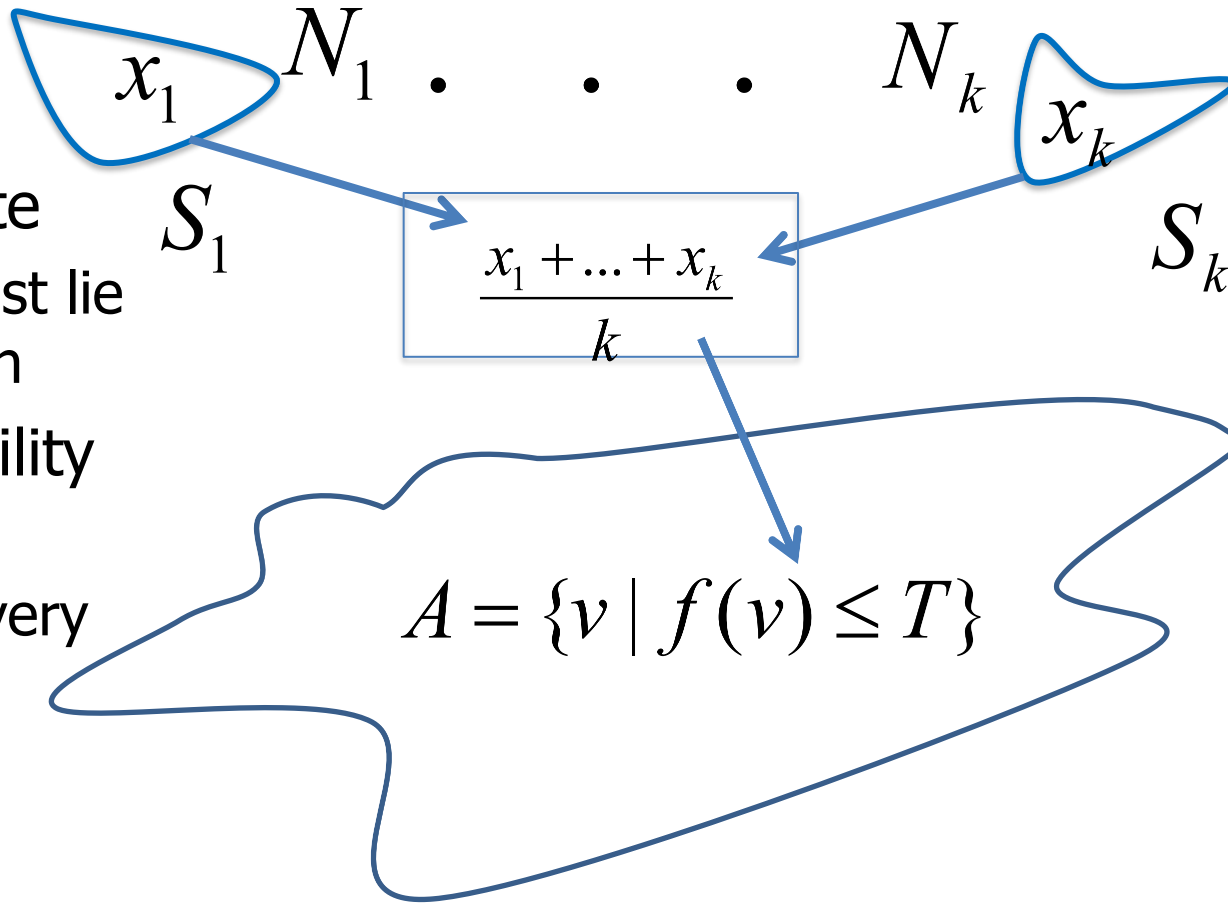


http://www.networkcoding.info/

https://buffy.eecs.berkeley.edu/PHP/resabs/resabs.php?f_year=2005&f_submit=chapgrp&f_chapter=1

The General SZ Problem

- *Different* SZs, per site
  - *Minkowski sum* must lie in admissible region
- Minimize the probability of local violations
  - **NP-hard** even in very simple cases!



- Heuristics for automated SZ construction
  - E.g., using hierarchical clustering of sites

Challenges, challenges, challenges…

- Distributed streaming versions of hard analytics functions (e.g., PageRank)?
- Geometric monitoring for Distributed CEP hierarchies?
  - Deal with uncertain events ("V" for Veracity)?
- Implementing GM ideas in scalable stream-processing engines (e.g., Storm)?
- CD machine learning to dynamically adapt to data/workload conditions?
  - Communication just one of our concerns
- Scalable analytics tools for streaming *time series*?

Conclusions

- Continuous querying of distributed streams is a natural model
  - Interesting space/time/communication tradeoffs
  - Captures several real-world applications
- **GM, SZs** : Generic geometric tools for monitoring complex queries
  - Sketches [VLDB’13], dynamic prediction models [SIGMOD’12, TODS’14], Skyline Monitoring [ICDE’14]
  - Novel insights through Convex Geometry [TKDE’14,VLDB’15]
- ***Much interesting algorithmic/systems work to be done!***

Thank you!

http://www.softnet.tuc.gr/~minos/

http://lift-eu.org , http://leads-project.eu

http://ferari-project.eu , http://qualimaster.eu

Current Big Data Projects @SoftNet

LEADS
LARGE-SCALE ELASTIC ARCHITECTURE FOR DATA AS A SERVICE

ICT STREP (2012-5)

http://leads-project.eu

FERARI

Flexible Event Processing for Big Data Architectures

ICT STREP (2014-7)

http://ferari-project.eu

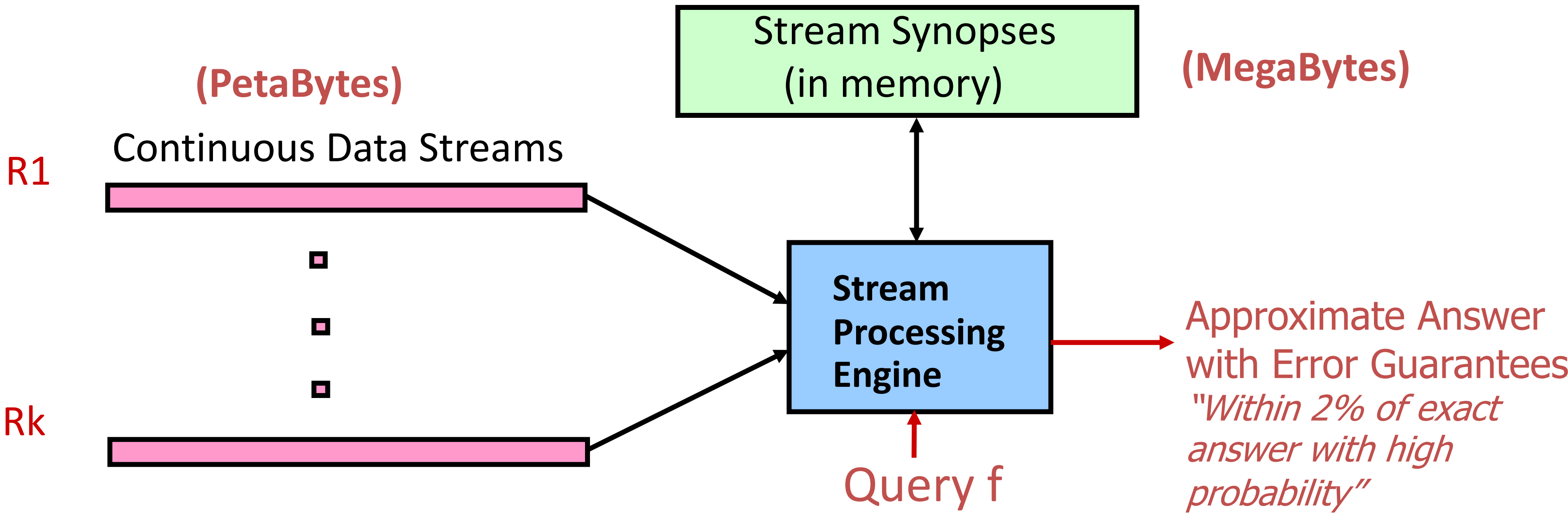
QualiMaster

Configurable, Autonomously-Adaptive Real-time Data Processing

ICT STREP (2014-7)

http://qualimaster.eu

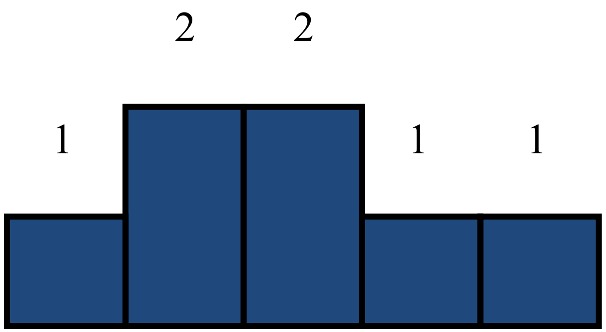
Stream Processing Model



- Approximate answers often suffice, e.g., trends, anomalies
- Requirements for stream synopses
  - *Single Pass:* Each record examined at most once, in arrival order
  - *Small Space:* Log or polylog in data stream size
  - *Small Time:* Per-record processing time must be low
  - Also: *Delete-proof, Composable*, …

SEVENTH FRAMEWORK PROGRAMME

AMS Sketches 101

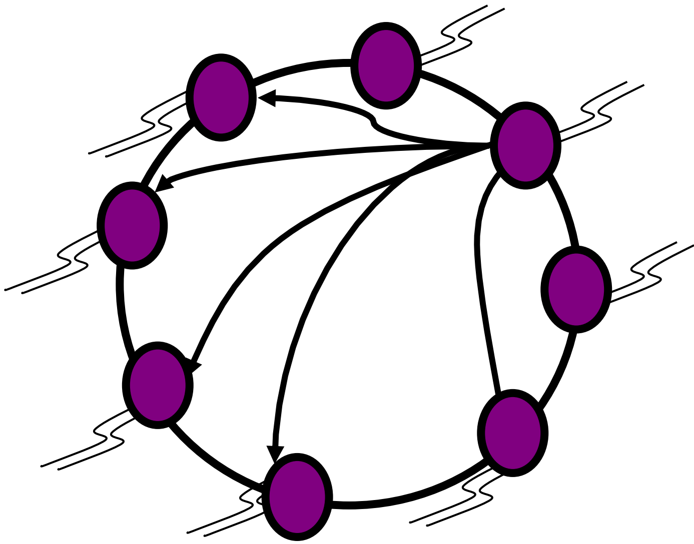


$$\{\xi_i\} \qquad \{\psi_i\}$$

$$sk(v) = \begin{bmatrix} X_1 = \sum_i v[i]\xi_i = \xi_1 + 2\xi_2 + 2\xi_3 + \xi_4 + \xi_5 \\ \vdots \\ X_k = \sum_i v[i]\psi_i \end{bmatrix}$$

- Simple randomized linear projections of data distribution
  - Easily computed over stream using logarithmic space
  - *Linear:* Compose through simple vector addition

CD Monitoring in Scalable Network Architectures



- E.g., DHT-based P2P networks
- Single query point
  - "Unfolding" the network gives hierarchy
  - But, single point of failure (i.e., root)
- Decentralized monitoring
  - Everyone participates in computation, all get the result
  - Exploit epidemics? Latency might be problematic…

Exploring the Prediction Model Space

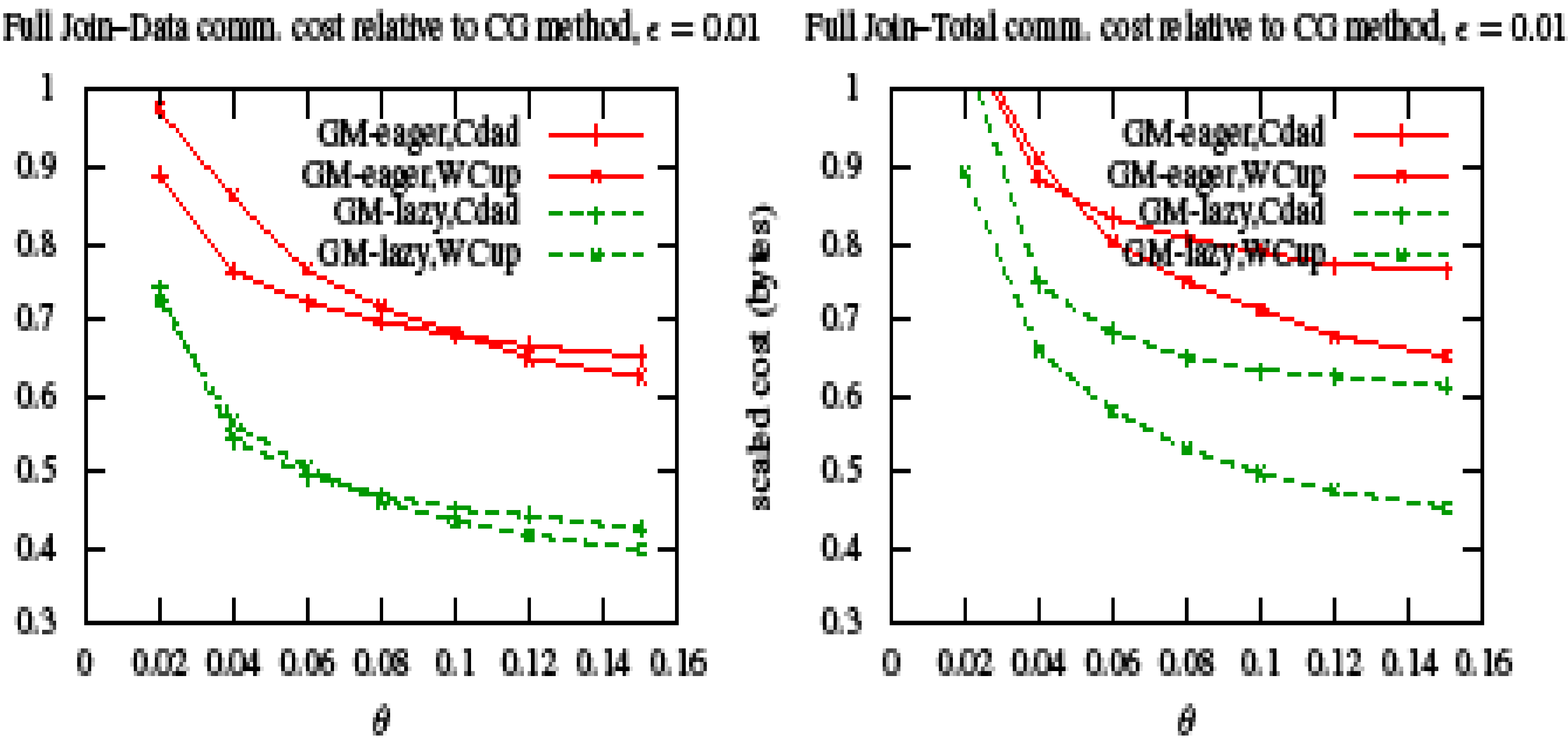
- The better we can capture and anticipate future stream direction, the less communication is needed
- So far, only look at predicting each stream alone
- Correlation/anti-correlation across streams should help?
  - But then, checking validity of model is expensive!
- Explore tradeoff-between power (expressiveness) of model and complexity (number of parameters)
  - Optimization via Minimum Description Length (MDL)? [Rissanen 1978]

Thank you!

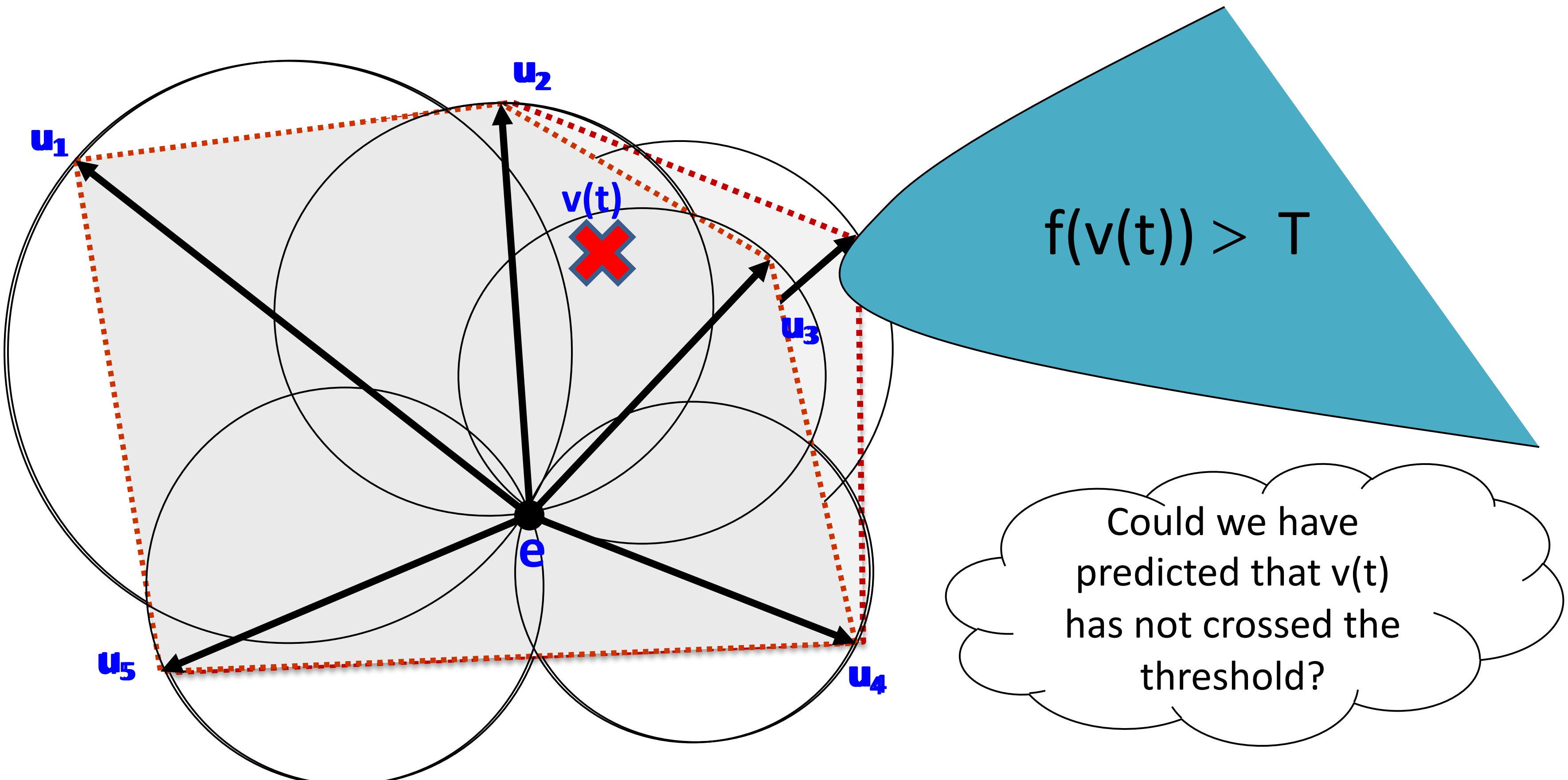
http://www.lift-eu.org/

http://www.softnet.tuc.gr/~minos/

Geometric Query Monitoring using AMS Sketches [GKS VLDB'13]



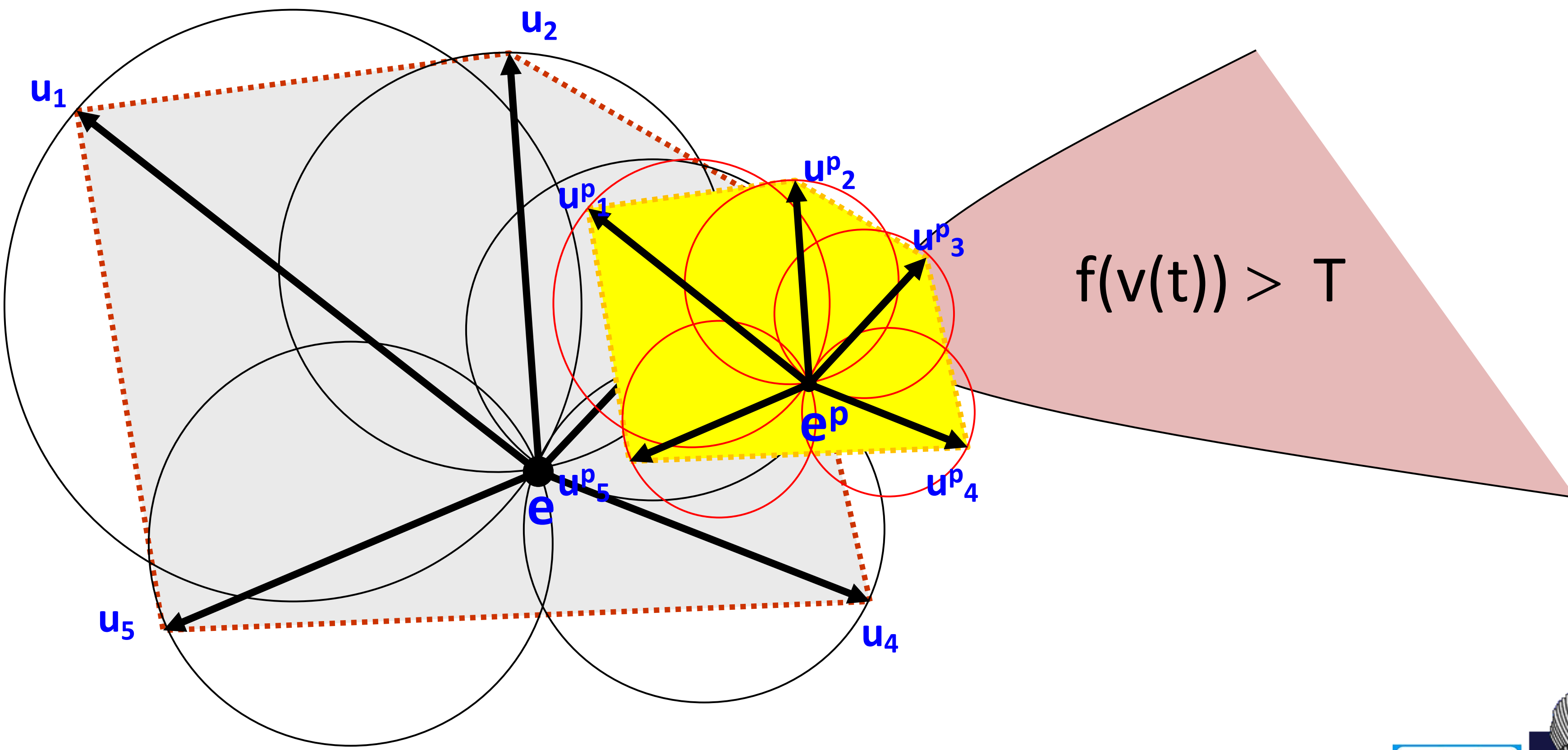
Prediction-based Geometric Threshold Monitoring [GDG SIGMOD'12, TODS'14]



SEVENTH FRAMEWORK PROGRAMME

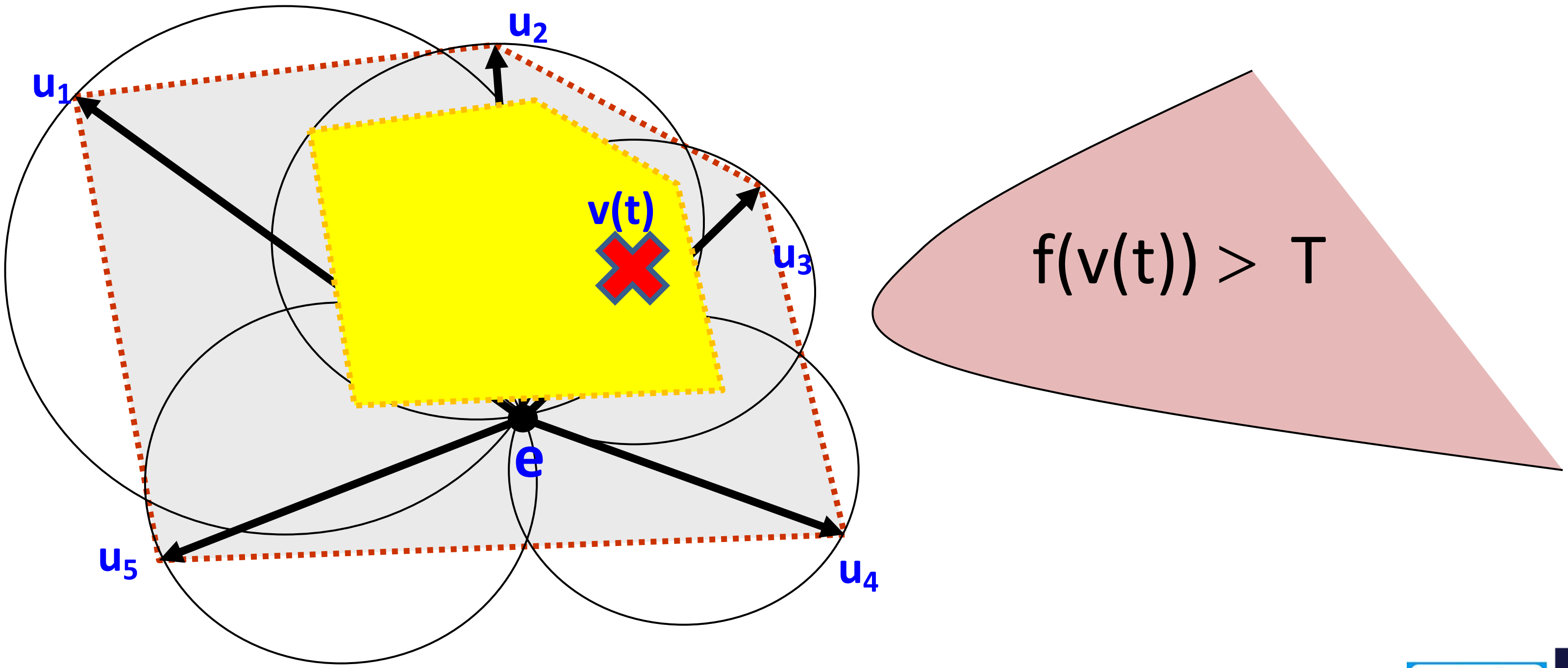
Issues

- Stricter local constraints do not guarantee less communication / lower false positives
- “Bad” scenarios may occur



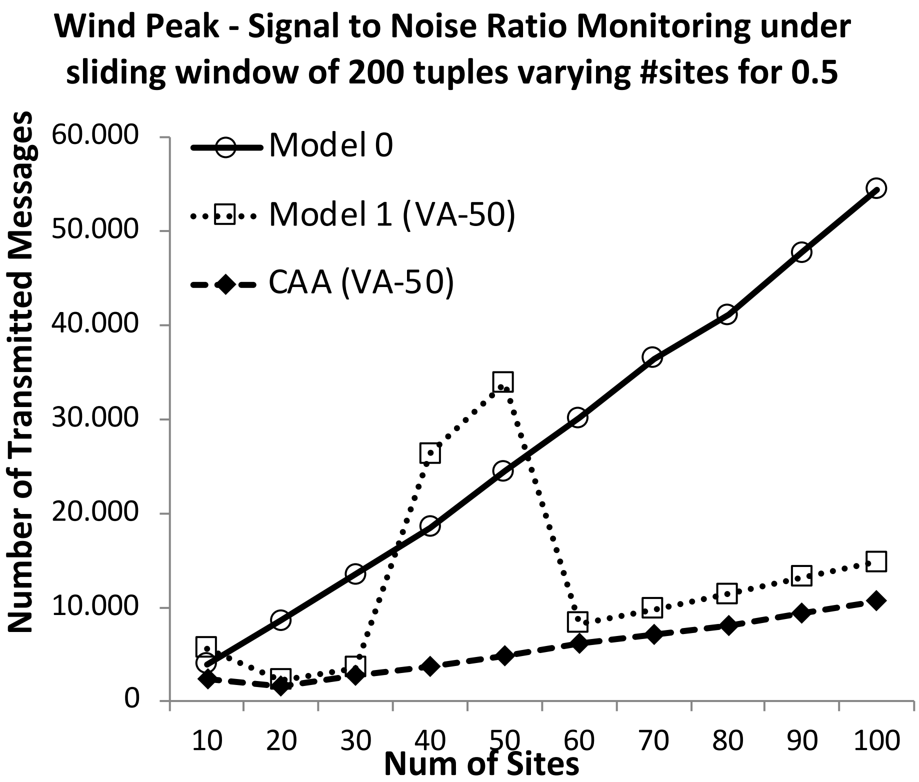
Towards Strong Geometric Monitoring Models

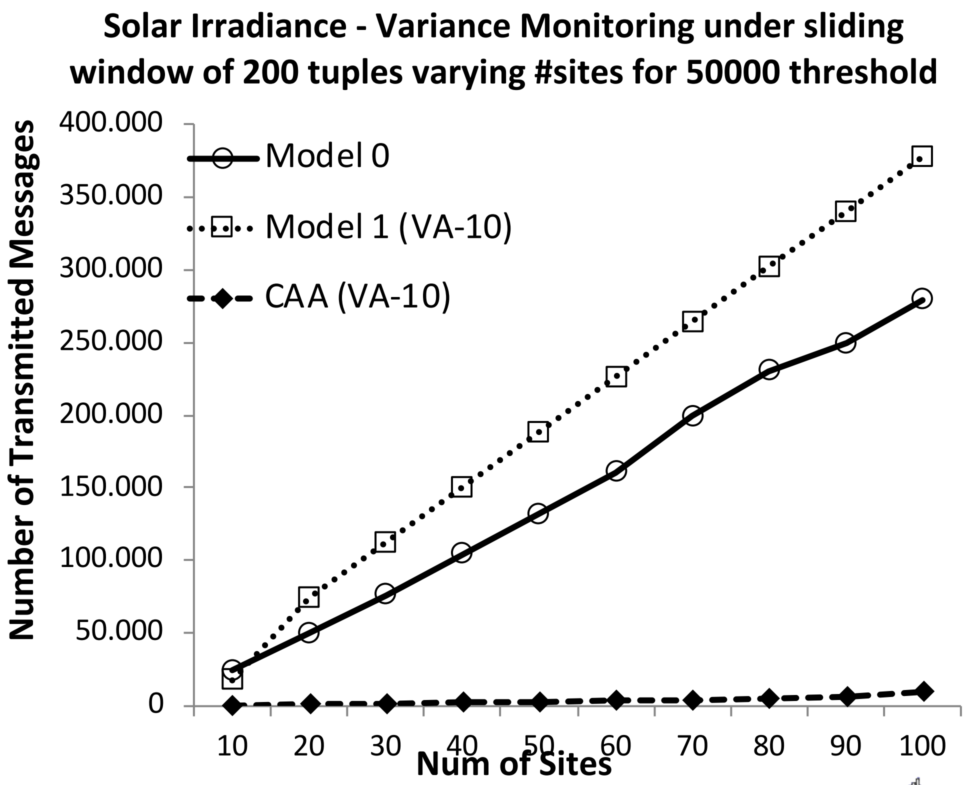
- **Containment of convex hulls:** hard to maintain/verify in distributed settings
- Designed several algorithms that try to approximately ensure containment with no/minimal information sharing
  - Based on combining static and prediction-based bounding regions



Some Experiments

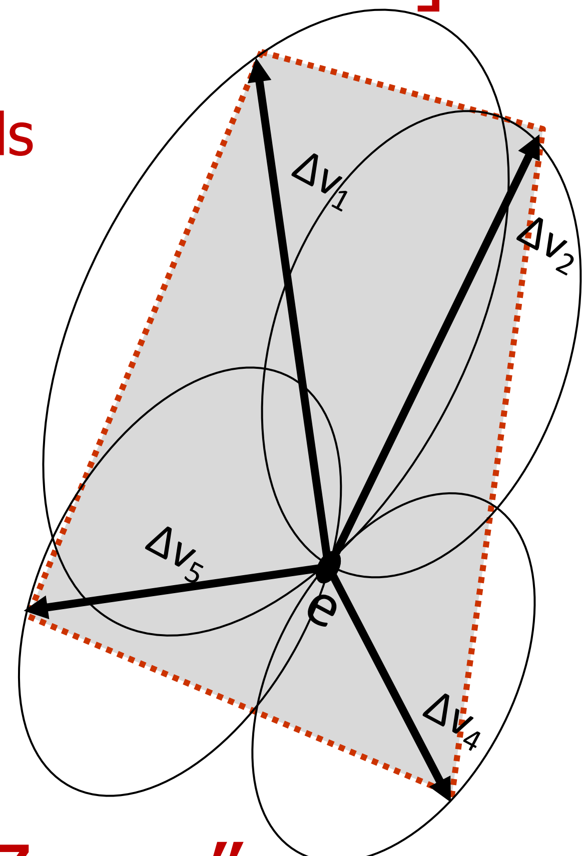
- Sliding Window
  - Up to 600 times lower cost compared to the basic GM





Extensions: Transforms, Shifts, Safe Zones

- Subsequent developments [SKS TKDE’12]
  - Same analysis of correctness holds when spheres are allowed to be ellipsoids
  - Different reference vectors can be used to increase radius when close to threshold values
  - Combining these observations allows additional cost savings



- More general theory of “Safe Zones”
  - Convex subsets of the admissible region