Mining Data Streams (Part 1)
New Topic: Infinite Data

High dim. data
- Locality sensitive hashing
- Clustering
- Dimensionality reduction

Graph data
- PageRank, SimRank
- Community Detection
- Spam Detection

Infinite data
- Filtering data streams
- Queries on streams
- Web advertising

Machine learning
- Decision Trees
- SVM
- Parallel SGD

Apps
- Recommender systems
- Association Rules
- Duplicate document detection
Data Streams

- In many data mining situations, we do not know the entire data set in advance
- **Stream Management** is important when the input rate is controlled *externally*:
  - Google queries
  - Twitter or Facebook status updates
- We can think of the data as **infinite** and **non-stationary** (the distribution changes over time)
  - This is the fun part and why interesting algorithms are needed
The Stream Model

- Input **elements** enter at a rapid rate, at one or more input ports (i.e., **streams**)
  - We call elements of the stream **tuples**

- The system cannot store the entire stream accessibly

- **Q:** How do you make critical calculations about the stream using a limited amount of (secondary) memory?
Stochastic Gradient Descent (SGD) is an example of a stream algorithm

In Machine Learning we call this: **Online Learning**

- Allows for modeling problems where we have a continuous stream of data
- We want an algorithm to learn from it and slowly adapt to the changes in data

**Idea: Do small updates to the model**

- **SGD** (SVM, Perceptron) makes small updates
- **So:** First train the classifier on training data
- **Then:** For every example from the stream, we slightly update the model (using small learning rate)
General Stream Processing Model

Streams Entering. Each stream is composed of elements/tuples

1, 5, 2, 7, 0, 9, 3
a, r, v, t, y, h, b
0, 0, 1, 0, 1, 1, 0

Limited Working Storage
Archival Storage

Processor

Ad-Hoc Queries
Standing Queries
Output

time
Types of queries one wants on answer on a data stream: (we’ll do these today)

- **Sampling data from a stream**
  - Construct a random sample

- **Queries over sliding windows**
  - Number of items of type $x$ in the last $k$ elements of the stream
Types of queries one wants on answer on a data stream: (we’ll do these on Thu)

- **Filtering a data stream**
  - Select elements with property $x$ from the stream

- **Counting distinct elements**
  - Number of distinct elements in the last $k$ elements of the stream

- **Estimating moments**
  - Estimate avg./std. dev. of last $k$ elements

- **Finding frequent elements**
Applications (1)

- **Mining query streams**
  - Google wants to know what queries are more frequent today than yesterday

- **Mining click streams**
  - Wikipedia wants to know which of its pages are getting an unusual number of hits in the past hour

- **Mining social network news feeds**
  - Look for trending topics on Twitter, Facebook
Applications (2)

- **Sensor Networks**
  - Many sensors feeding into a central controller

- **Telephone call records**
  - Data feeds into customer bills as well as settlements between telephone companies

- **IP packets monitored at a switch**
  - Gather information for optimal routing
  - Detect denial-of-service attacks
Sampling from a Data Stream: Sampling a fixed proportion

As the stream grows the sample also gets bigger
Sampling from a Data Stream

- Since we can not store the entire stream, one obvious approach is to store a sample.
- Two different problems:
  - (1) Sample a fixed proportion of elements in the stream (say 1 in 10)
  - (2) Maintain a random sample of fixed size over a potentially infinite stream
    - At any “time” $k$ we would like a random sample of $s$ elements
    - What is the property of the sample we want to maintain?
      For all time steps $k$, each of $k$ elements seen so far has equal prob. of being sampled
Problem 1: Sampling fixed proportion

Scenario: Search engine query stream
- Stream of tuples: (user, query, time)
- Answer questions such as: How often did a user run the same query in a single day
- Have space to store $1/10^{th}$ of query stream

Naïve solution:
- Generate a random integer in $[0...9]$ for each query
- Store the query if the integer is 0, otherwise discard
Problem with Naïve Approach

- **Simple question:** What fraction of unique queries by an average search engine user are duplicates?
  - Suppose each user issues \( x \) queries once and \( d \) queries twice (total of \( x+2d \) query instances)
    - **Correct answer:** \( \frac{d}{x+d} \)
  - **Proposed solution:** We keep 10% of the queries
    - Sample will contain \( \frac{x}{10} \) of the singleton queries and \( \frac{2d}{10} \) of the duplicate queries at least once
    - But only \( \frac{d}{100} \) pairs of duplicates
      - \( \frac{d}{100} = \frac{1}{10} \cdot \frac{1}{10} \cdot d \)
      - Of \( d \) “duplicates” \( \frac{18d}{100} \) appear exactly once
        - \( \frac{18d}{100} = \left( \left( \frac{1}{10} \cdot \frac{9}{10} \right) + \left( \frac{9}{10} \cdot \frac{1}{10} \right) \right) \cdot d \)
    - So the sample-based answer is
      \[
      \frac{\frac{d}{100}}{\frac{x}{10} + \frac{d}{100} + \frac{18d}{100}} = \frac{d}{10x+19d}
      \]
Solution: Sample Users

Solution:

- Pick 1/10\textsuperscript{th} of users and take all their searches in the sample

- Use a hash function that hashes the user name or user id uniformly into 10 buckets
Stream of tuples with keys:
- Key is some subset of each tuple’s components
  - e.g., tuple is (user, search, time); key is user
- Choice of key depends on application

To get a sample of $a/b$ fraction of the stream:
- Hash each tuple’s key uniformly into $b$ buckets
- Pick the tuple if its hash value is at most $a$

Hash table with $b$ buckets, pick the tuple if its hash value is at most $a$.

How to generate a 30% sample?
Hash into $b=10$ buckets, take the tuple if it hashes to one of the first 3 buckets
Sampling from a Data Stream: Sampling a fixed-size sample

As the stream grows, the sample is of fixed size
Problem 2: Fixed-size sample

Suppose we need to maintain a random sample $S$ of size exactly $s$ tuples

- E.g., main memory size constraint

Why? Don’t know length of stream in advance

Suppose by time $n$ we have seen $n$ items

- Each item is in the sample $S$ with equal prob. $s/n$

How to think about the problem: say $s = 2$

Stream: $[a, x, c, y, z, k, c, d, e, g, ...$

At $n = 5$, each of the first 5 tuples is included in the sample $S$ with equal prob.
At $n = 7$, each of the first 7 tuples is included in the sample $S$ with equal prob.

Impractical solution would be to store all the $n$ tuples seen so far and out of them pick $s$ at random
Solution: Fixed Size Sample

- **Algorithm (a.k.a. Reservoir Sampling)**
  - Store all the first $s$ elements of the stream to $S$
  - Suppose we have seen $n-1$ elements, and now the $n^{th}$ element arrives ($n > s$)
    - With probability $s/n$, keep the $n^{th}$ element, else discard it
    - If we picked the $n^{th}$ element, then it replaces one of the $s$ elements in the sample $S$, picked uniformly at random

- **Claim:** This algorithm maintains a sample $S$ with the desired property:
  - After $n$ elements, the sample contains each element seen so far with probability $s/n
We prove this by induction:

- Assume that after $n$ elements, the sample contains each element seen so far with probability $s/n$
- We need to show that after seeing element $n+1$ the sample maintains the property
  - Sample contains each element seen so far with probability $s/(n+1)$

Base case:

- After we see $n=s$ elements the sample $S$ has the desired property
  - Each out of $n=s$ elements is in the sample with probability $s/s = 1$
Inductive hypothesis: After $n$ elements, the sample $S$ contains each element seen so far with prob. $s/n$

Now element $n+1$ arrives

Inductive step: For elements already in $S$, probability that the algorithm keeps it in $S$ is:

\[
\left(1 - \frac{s}{n+1}\right) + \left(\frac{s}{n+1}\right)\left(\frac{s-1}{s}\right) = \frac{n}{n+1}
\]

So, at time $n$, tuples in $S$ were there with prob. $s/n$

Time $n \rightarrow n+1$, tuple stayed in $S$ with prob. $n/(n+1)$

So prob. tuple is in $S$ at time $n+1 = \frac{s \cdot n}{n \cdot n+1} = \frac{s}{n+1}$
Queries over a (long) Sliding Window
A useful model of stream processing is that queries are about a window of length $N$ – the $N$ most recent elements received.

**Interesting case:** $N$ is so large that the data cannot be stored in memory, or even on disk.
- Or, there are so many streams that windows for all cannot be stored.

**Amazon example:**
- For every product $X$ we keep a 0/1 stream of whether that product was sold in the $n$-th transaction.
- We want answer queries, how many times have we sold $X$ in the last $k$ sales.
Sliding Window on a single stream:

q w e r t y u i o p a s d f g h j k l z x c v b n m

q w e r t y u i o p a s d f g h j k l z x c v b n m

q w e r t y u i o p a s d f g h j k l z x c v b n m

q w e r t y u i o p a s d f g h j k l z x c v b n m

Past  Future

N = 6
Problem:
- Given a stream of 0s and 1s
- Be prepared to answer queries of the form
  How many 1s are in the last \( k \) bits? For any \( k \leq N \)

Obvious solution:
Store the most recent \( N \) bits
- When new bit comes in, discard the \( N+1 \)st bit

Suppose \( N=6 \)

0 1 0 0 1 1 0 1 1 1 0 1 0 1 0 1 1 0 1 1 0 1 1 0

<table>
<thead>
<tr>
<th>Past</th>
<th>Future</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 1 0 0 1 1 0 1 1 1 0 1 0 1 0 1 1</td>
<td>1 1 0 1 1 0</td>
</tr>
</tbody>
</table>
You can not get an exact answer without storing the entire window

**Real Problem:**
What if we cannot afford to store $N$ bits?
- We’re processing 1B streams and is $N=1B$ as well

But we are happy with an approximate answer
An attempt: Simple solution

- **Q:** How many 1s are in the last $N$ bits?
- A simple solution that does not really solve our problem: Uniformity assumption

Maintain 2 counters:
- $S$: number of 1s from the beginning of the stream
- $Z$: number of 0s from the beginning of the stream

How many 1s are in the last $N$ bits? $N \cdot \frac{S}{S+Z}$

But, what if stream is non-uniform?
- What if distribution changes over time?
DGIM Method

- DGIM solution that does **not** assume uniformity
- We store $O(\log^2 N)$ bits per stream
- Solution gives approximate answer, never off by more than 50%:
  - Error factor can be reduced to any fraction $> 0$, with more complicated algorithm and proportionally more stored bits
    - Error: If we have 10 1s then 50% error means 10 +/- 5
Idea: Exponential Windows

- **Solution that doesn’t (quite) work:**
  - Summarize **exponentially increasing** regions of the stream, looking backward
  - Drop small regions if they begin at the same point as a larger region

We can reconstruct the count of the last $N$ bits, except we are not sure how many of the last 6 1s are included in the $N$. 

Window of width 16 has 6 1s

There are 10+2+1 1s here

There are 4+2+1 1s here

0 1 0 0 1 1 1 0 0 0 1 0 1 0 0 1 0 0 0 1 0 1 1 0 1 1 0 1 1 1 0 0 1 0 1 0 1 1 0 0 1 1 0 1 0

N

2/26/19

Stores only $O(\log^2 N)$ bits
- $O(\log N)$ counts of $\log_2 N$ bits each

Easy update as more bits enter

Error in count no greater than the number of 1s in the “unknown” area
As long as the 1s are fairly evenly distributed, the error due to the unknown region is small – no more than 50%.

But it could be that all the 1s are in the unknown area at the end.

In that case, the error is unbounded!
**Fixup: DGIM method**

- **Idea:** Instead of summarizing fixed-length blocks, summarize blocks with specific number of 1s:
  - Let the block **sizes** (number of 1s) increase exponentially

- **When there are few 1s in the window, block sizes stay small, so errors are small**

![Binary Blocks Example](image-url)
DGIM: Timestamps

- Each bit in the stream has a timestamp, starting 1, 2, ...
- Record timestamps modulo $N$ (the window size), so we can represent any relevant timestamp in $O(\log_2 N)$ bits
DGIM: Buckets

- A bucket in the DGIM method is a record consisting of:
  - (A) The timestamp of its end \([O(\log N)\text{ bits}]\)
  - (B) The number of 1s between its beginning and end \([O(\log \log N)\text{ bits}]\)

- **Constraint on buckets:**
  Number of 1s must be a power of 2
  - That explains the \(O(\log \log N)\) in (B) above
Either one or two buckets with the same power-of-2 number of 1s

- Buckets do not overlap in timestamps
- Buckets are sorted by size
  - Earlier buckets are not smaller than later buckets
- Buckets disappear when their end-time is > $N$ time units in the past
Example: Bucketized Stream

At least 1 of size 16. Partially beyond window.

Three properties of buckets that are maintained:
- Either one or two buckets with the same power-of-2 number of 1s
- Buckets do not overlap in timestamps
- Buckets are sorted by size
Updating Buckets (1)

- When a new bit comes in, drop the last (oldest) bucket if its end-time is prior to $N$ time units before the current time.

- 2 cases: Current bit is 0 or 1

- If the current bit is 0: no other changes are needed
If the current bit is 1:

1. Create a new bucket of size 1, for just this bit
   - End timestamp = current time
2. If there are now three buckets of size 1, combine the oldest two into a bucket of size 2
3. If there are now three buckets of size 2, combine the oldest two into a bucket of size 4
4. And so on ...
Example: Updating Buckets

Current state of the stream:

```
10010101100010110101010101010110101010101110101010111010100010110010
```

Bit of value 1 arrives

```
0010101100010110101010101010110101010101110101010111010100010110010
```

Two orange buckets get merged into a yellow bucket

```
0010101100010110101010101010110101010101110101010111010100010110010
```

Next bit 1 arrives, new orange bucket is created, then 0 comes, then 1:

```
01011000101101010101010101101010101011101010101110101000101100101101
```

Buckets get merged…

```
01011000101101010101010101101010101011101010101110101000101100101101
```

State of the buckets after merging

```
01011000101101010101010101101010101011101010101110101000101100101101
```
To estimate the number of 1s in the most recent $N$ bits:

1. Sum the sizes of all buckets but the last
   (note “size” means the number of 1s in the bucket)
2. Add half the size of the last bucket

Remember: We do not know how many 1s of the last bucket are still within the wanted window
Example: Bucketized Stream

At least 1 of size 16. Partially beyond window.

\[ \text{1001010110001011010101010101011010101010101110101010111010100010110010} \]

2 of size 8

2 of size 4

1 of size 2

2 of size 1
- **Why is error 50%? Let’s prove it!**
- Suppose the last bucket has size $2^r$
- Then by assuming $2^{r-1}$ (i.e., half) of its $1$s are within the last window (but out of last-$N$ bits), we make an error of at most $2^{r-1}$
- Since there is at least one bucket of each of the sizes less than $2^r$, the true sum is at least $1 + 2 + 4 + .. + 2^{r-1} = 2^r - 1$
- Thus, error at most **50%**
Further Reducing the Error

- Instead of maintaining 1 or 2 of each size bucket, we allow either $r-1$ or $r$ buckets ($r > 2$)
  - Except for the largest size buckets; we can have any number between 1 and $r$ of those
- Error is at most $O(1/r)$
- By picking $r$ appropriately, we can tradeoff between number of bits we store and the error
Can we use the same trick to answer queries 

**How many 1's in the last** \( k \) **? where** \( k < N \)?

- **A:** Find earliest bucket \( B \) that at overlaps with \( k \). 
  Number of 1s is the **sum of sizes of more recent buckets** + \( \frac{1}{2} \) size of \( B \)

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Can we handle the case where the stream is not bits, but integers, and we want the sum of the last \( k \) elements?
Stream of positive integers
We want the sum of the last $k$ elements

- **Amazon**: Avg. price of last $k$ sales

**Solution:**

1. If you know all have at most $m$ bits
   - Treat $m$ bits of each integer as a separate stream
   - Use DGIM to count 1s in each integer/stream
   - The sum is $\sum_{i=0}^{m-1} c_i 2^i$

2. Use buckets to keep partial sums
   - Sum of elements in size $b$ bucket is at most $2^b$

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$c_i$...estimated count for $i$-th bit

<table>
<thead>
<tr>
<th>2 5 7 1 3 8 4 6 7 9 1 3 7</th>
<th>6 5 3 5 7 1 3 3 1 2 2 6</th>
</tr>
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<td>3 5 7 1 3 3 1 2 2 6 3</td>
</tr>
</tbody>
</table>

Idea: Sum in each bucket is at most $2^b$ (unless bucket has only 1 integer)
Max bucket sum:
Summary

- **Sampling a fixed proportion of a stream**
  - Sample size grows as the stream grows
- **Sampling a fixed-size sample**
  - Reservoir sampling
- **Counting the number of 1s in the last N elements**
  - Exponentially increasing windows
  - Extensions:
    - Number of 1s in any last k (k < N) elements
    - Sums of integers in the last N elements