Data Validation at Scale

Managing Data Quality in Complex Data Pipelines

DB / DC 2023, Munich, Germany
December 05, 2023
Wolle

Material Available at https://wolle.science
I Am Wolle

Research:
• Stream Processing
• Real-Time Databases
• NoSQL & Cloud Systems
• ...

Practice:
• Web Caching
• Big Data Analytics
• Anger Management
• ...

Universität Hamburg
Carl von Ossietzky Universität Oldenburg
Bagend
The Importance of Data Validation
Where is data validation integrated into data science pipelines and what is its impact?

Data Quality & Constraints
What dimensions of data quality are there and how can they be ensured?

Scalability-Related Challenges
Why is data validation difficult in data-intensive domains?
Running **Example**: Web Performance Analysis Pipeline

Collection | Ingestion | Analytics | Reporting
---|---|---|---
Tracking (RUM) | | | Performance Dashboard
| | | QA Dashboard
| | | Real-Time Alerting
| | | Ad-hoc SQL Interface
| | | Custom Reporting

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Felix Gessert. *Batching Was Yesterday: Real-Time Tracking & Analysis For 100+ Million Visitors*. code.talks (2023)

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Running **Example**: Web Performance Analysis Pipeline

Collection → Ingestion → Analytics → Reporting

- **Collection**
  - Tracking (RUM)

- **Ingestion**
  - Flink

- **Analytics**
  - SQL Interface

- **Reporting**
  - Performance Dashboard
  - QA Dashboard
  - Real-Time Alerting
  - Ad-hoc SQL Interface
  - Custom Reporting

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Running **Example**: Web Performance Analysis Pipeline

1. Tracking (RUM)
2. Cloud
3. Database
4. Insight
Running Example: Web Performance Analysis Pipeline

Collection

Ingestion

Processing & Storage

Analysis, Reporting & ML

Tracking (RUM)

Dashboarding

Data Warehousing

Machine Learning

Slides: wolle.science/data-validation

Wolfram Wingerath (Munich, December 05, 2023)
• **Goal:** verify that data in the pipeline is in an acceptable state for downstream processing, e.g.
  
  o External reporting (statistics, visualizations & dashboarding)
  
  o Internal reporting (debugging, product optimizations)
  
  o Decision-making (analytics, machine learning)

• Data validation can be integrated **in and between all stages**
There are different **dimensions of data quality**, especially:

- **Completeness**: Do we have all the data we need to assess page load performance?
- **Consistency**: Does data have a valid format and does it comply with business semantics?
- **Accuracy**: Do data items represent their corresponding real-world entities well?
- **Uniqueness**: Are duplicate records known and are all unique attributes actually distinct?
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1st PI (Page Impression)

2nd PI

Unload Beacon

Unload Beacon

Data sometimes just gets lost!

- Is beacon loss a problem at all?
- **When** is beacon loss a problem?
  - For which beacon types? For which beacon strategies?
- **Where** is beacon loss a problem?
  - For which browsers? For which device types?
Unload Beacon Reliability by Strategy

```javascript
addEventListener("unload", (event) => {
    navigator.sendBeacon(url, JSON.stringify(data));
});
```

Available on all platforms

```javascript
addEventListener("beforeunload", (event) => {
    navigator.sendBeacon(url, JSON.stringify(data));
});
```

Experimental feature (only available as origin trial in Chrome)

```javascript
addEventListener("pagehide", (event) => {
    navigator.sendBeacon(url, JSON.stringify(data));
});
```

```javascript
var beacon = new window.PendingPostBeacon(
    url,
    {
        timeout: 60000,
        backgroundTimeout: 0
    });
beacon.setData(JSON.stringify(data));
```
Unload Beacon Reliability by Strategy

```javascript
addEventListener("unload", (event) => {
  navigator.sendBeacon(url, JSON.stringify(data));
});
```

Available on all platforms

```javascript
addEventListener("beforeunload", () => {
  navigator.sendBeacon(url, JSON.stringify(data));
});
```

```javascript
addEventListener("pageshow", () => {
  navigator.sendBeacon(url, JSON.stringify(data));
});
```

```javascript
if (document.visibilityState === "hidden") {
  navigator.sendBeacon(url, JSON.stringify(data));
}
```

```
beacon.setData(JSON.stringify(data));
```

Wolfram Wingerath (Munich, December 05, 2023) slides: wolle.science/data-validation
Unload Beacon Reliability by Strategy & Device

<table>
<thead>
<tr>
<th>Strategy</th>
<th>MOBILE</th>
<th>DESKTOP</th>
</tr>
</thead>
<tbody>
<tr>
<td>PendingPostBeacon</td>
<td>97%</td>
<td>99%</td>
</tr>
<tr>
<td>visibilitychange</td>
<td>90%</td>
<td>91%</td>
</tr>
<tr>
<td>pagehide</td>
<td>81%</td>
<td>88%</td>
</tr>
<tr>
<td>unload</td>
<td>78%</td>
<td>87%</td>
</tr>
<tr>
<td>beforeunload</td>
<td>28%</td>
<td>73%</td>
</tr>
</tbody>
</table>

Based on 52 million page views on a globally operating e-commerce site measured by Speed Kit's real user-monitoring | August 2023

Desktop data may be overrepresented!
## Unload Beacon Reliability by Strategy & Browser

<table>
<thead>
<tr>
<th></th>
<th>Chrome</th>
<th>Safari</th>
<th>Firefox</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pending PostBeacon</strong></td>
<td>98%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td><strong>Visibility change</strong></td>
<td>92%</td>
<td>89%</td>
<td>95%</td>
</tr>
<tr>
<td><strong>PageHide</strong></td>
<td>88%</td>
<td>80%</td>
<td>91%</td>
</tr>
<tr>
<td><strong>Unload</strong></td>
<td>86%</td>
<td>80%</td>
<td>90%</td>
</tr>
<tr>
<td><strong>Before Unload</strong></td>
<td>83%</td>
<td>3%</td>
<td>91%</td>
</tr>
</tbody>
</table>

Based on 52 million page views on a globally operating e-commerce site measured by Speed Kit real user-monitoring | August 2023

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Erik Witt. Unload Beacon Reliability: Benchmarking Strategies for Minimal Data Loss, Speed Kit Tech Blog (2023)
Unload Beacon **Reliability**: The Ideal Combo Strategy

Based on 52 million page views on a globally operating e-commerce site measured by Speed Kit’s real user-monitoring | August 2023

Can be used with Backward-Forward Cache?

- `visibilitychange + pagehide + beforeunload + unload`
  - 91.7%
  - ✗

- `visibilitychange + pagehide + beforeunload`
  - 91.7%
  - ✗

- `visibilitychange + pagehide`
  - 91.3%
  - ✓

References:

There are different dimensions of data quality, especially:

- **Completeness**: Do we have all the data we need to assess page load performance?
- **Consistency**: Does data have a valid format and does it comply with business semantics?
- **Accuracy**: Do data items represent their corresponding real-world entities well?
- **Uniqueness**: Are duplicate records known and are all unique attributes actually distinct?

### Dimensions of Data Quality: Consistency

<table>
<thead>
<tr>
<th>Timestamp</th>
<th>Pageload ID</th>
<th>Browser</th>
<th>LCP (Performance)</th>
<th>Session ID</th>
<th>URL</th>
</tr>
</thead>
<tbody>
<tr>
<td>09:05:04.578</td>
<td>37ab08</td>
<td>Edge</td>
<td>&quot;670ms&quot;</td>
<td>123</td>
<td>null</td>
</tr>
<tr>
<td>13:26:48.139</td>
<td>9cddf7</td>
<td>Firefox</td>
<td>692 654</td>
<td>456</td>
<td>abc.de/red</td>
</tr>
<tr>
<td>13:28:23.857</td>
<td>0b577a</td>
<td>Firefox</td>
<td>0.256</td>
<td>456</td>
<td>abc.de/blue</td>
</tr>
<tr>
<td>13:29:17.468</td>
<td>faf55e</td>
<td>Edge</td>
<td>1.598</td>
<td>456</td>
<td>abc.de/sold</td>
</tr>
<tr>
<td>20:45:38.941</td>
<td>faf55e</td>
<td>null</td>
<td>null</td>
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**Note**: Browser values should be unified for all records in the same session!
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**Note**: Browser values should be unified for all records in the same session! → value may be replaced with majority vote (another reasonable option: replace old values with latest one)
Dimensions of Data Quality:

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Note: All values represent milliseconds, but formats differ depending on browser.
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**Note**: All values represent milliseconds, but formats differ depending on browser. → values may be converted to integer.
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**Note**: Despite being in the right format, one value does not represent a reasonable timer value.
There are different dimensions of data quality, especially:

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Note: Despite being in the right format, one value does not represent a reasonable timer value. → broken value may be removed.
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Note: The ID field should be unique, but two different records share the same value!
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**Note**: The ID field should be unique, but two different records share the same value! → merge duplicates into a single record
• **Constraints** are rules, conditions, or limits that data must adhere to

• **Type Checks** represent expectations on the data format, e.g.
  - *Value range* for numerical data (e.g. [0,\(\text{MAX}\_\text{INTEGER}\)) for load timers)
  - *Format or pattern* for string-valued data (e.g. ISO 8601 for timestamps)
  - *Structure* for complex attributes (e.g. required keys for JSON objects)

• **Complex conditions** can further describe complex semantics such as
  - Cross-field or cross-record relationships (e.g. same browser within sessions)
  - Referential integrity between records in different collections
  - Custom constraints for domain semantics
import pandas as pd
import pandera as pa
from pandera import Column, DataFrameSchema, Check

# Define the schema
schema = DataFrameSchema(
    {
        "Timestamp": Column(pa.DateTime),
        "Pageload ID": Column(pa.String,
            Check(lambda x: x.str.len() == 8)),
        "Browser": Column(pa.String,
            Check(lambda x: x.isin(['Chrome', 'Edge', 'Firefox']))),
        "LCP": Column(pa.Int,
            Check(lambda x: (x >= 0) & (x <= 600000))),
        "Session ID": Column(pa.Int),
    }
)
# valid data item

good = {
    "Timestamp": [pd.Timestamp("2023-05-10 13:26:48.139")],
    "PageLoad ID": ["9cddf7"],
    "Browser": ["Firefox"],
    "LCP": [256],
    "Session ID": [456],
}

# invalid data item

bad = {
    "Timestamp": [pd.Timestamp("2023-05-10 09:05:04.578")],
    "PageLoad ID": ["37ab08"],
    "Browser": ["Edge"],
    "LCP": [692654],  # timer value out of bounds
    "Session ID": [123],
}
for record in [good, bad]:
    record_id = record['Pageload ID'][0]
    try:
        validated = schema(pd.DataFrame(record))
        print(f"Validation passed for record {record_id}!
"
    except pa.errors.SchemaError as e:
        print(f"Validation FAILED for record {record_id}:")
        print(e)

Validation passed for record 9cddf7!

Validation FAILED for record 37ab08
<Schema Column(name=LCP, type=DataType(int64))> failed element-wise validator 0:
<Check <lambda>>
failure cases:
    index  failure_case
    0      0  692654
Fundamental Challenge: Scalability

One Month in Data Errors at Baqend: April 2023

Data Errors by Type
- Aggregation (66.89%)
- Attribute (32.93%)
- Internal (0.16%)

Data Errors by Cause
- MissingValue (63.91%)
- BlankValue (11.92%)
- ValueOutOfRange (8.50%)
- AmbiguousValue (7.98%)
- StringLengthExceeded (4.30%)
- Other (2.46%)
### Challenging at Scale: Complexity

- Manual constraint definition is often infeasible, because of...
  - inherent data complexity (often hundreds of attributes)
  - aggregation, derived storage, and evolving schemas
  - a plethora of other data stores to integrate!

→ **Automation** is necessary!
Computing validation metrics from scratch periodically can be infeasible, because of ...

- ... strict timing requirements
- ... efficiency or cost reasons
- ... data privacy reasons

→ Incremental computation can be the only option!

Details in Felix’ talk!
Specifying generalized constraints can be difficult in large deployments, because of ...

- ... temporal fluctuations (e.g. throughout the day, on black Friday, or during holidays)
- ... multi-tenancy (e.g. different data patterns by customer timezone or domain)

→ **Elasticity & Multi-Tenancy** requirements can be challenging!
Deployments can break things (and cause sudden load spikes for validation)

- **Availability**: Can this take down your data pipeline?
- **Attribution**: Who or what is causing the problem?
- **Responsibility**: Can you fix the problem?
So How Do You Handle All This?

- **Advanced Techniques**
  - Inferring constraints
  - Adapting to schema changes
  - Incremental computation of complex measures

- **Tooling & Frameworks**
  - Validation libraries such as Great Expectations, Pandera, TFDV, or Deequ
  - Preprocessing and validation with Apache Spark and Apache Flink

- **Further Challenges**
  - Handling distribution (validation per partitioning, avoiding skew, ...)
  - Efficiency and performance (load distribution, approximation, ...)
  - Operational challenges (anomaly detection, fixing, load shedding, ...)

Wolfram Wingerath (Munich, December 05, 2023)
• **Data Quality** can be measured along dimensions such as completeness, consistency, accuracy, and uniqueness

• **Constraints** specify expectations about the data and can be used to enforce them

• **Data Validation** is the process of ensuring high data quality for processes like analysis, modeling, and decision-making

• Data Validation **Challenges at Scale** include
  
  o **Complexity**: schemas are often too complex to define constraints manually
  
  o **Volatility**: data varies throughout the day, by season, or by customer
  
  o **Continuity**: incremental processing is required when computation from scratch is infeasible
Thanks! Questions?

Material Available at https://wolle.science