# Streaming & Pipeline Processing

## Event Time, Windows, State, and Reliable Delivery

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# Learning Objectives

By the end, participants can:

- Explain event time vs processing time and watermarks.
- Choose windowing strategies and triggers for different problems.
- Design stateful operators and manage late/duplicate data.
- Reason about delivery guarantees and end-to-end exactly-once.
- Join streams and handle backpressure safely.
- Test, observe, and operate streaming pipelines in production.

# Agenda *(5 min)*

1. Why Streaming? *(10 min)*
2. Time Model: Event vs Processing Time & Watermarks *(15 min)*
3. Windows, Triggers, Lateness *(20 min)*
4. Stateful Processing & Delivery Guarantees *(20 min)*
5. Joins, Backpressure, Fault Tolerance *(15 min)*
6. Testing, Observability, Cost *(10 min)*
7. Exercises & Wrap-up *(10 min)*

# Motivation *(10 min)*

- Many domains are **event-driven**: telemetry, payments, logs, sensors.
- Streaming yields **low latency** insights and reactive products.
- Unified batch+stream architectures reduce duplication and staleness.
- Cost/ops trade-offs: continuous compute vs scheduled batch.

# Event Time vs Processing Time *(8 min)*

- **Event Time**: when an event actually happened.
- **Processing Time**: when the system observed it.
- Networks, buffers, and clocks cause reordering and delay.

# Watermarks *(7 min)*

- A **watermark** asserts that most events older than $T$ have arrived.
- Drives window completeness and trigger firing.
- Heuristics: fixed lag (e.g., eventTime - 2 min), source-derived, or adaptive.

# Timestamp Assignment *(5 min)*

```
source("clicks")
  .assignTimestamp(event.ts)      // choose event time field
  .watermark(event.ts - 120s)     // simple fixed-lag watermark
  .map(...)
  .sink("analytics")
```

# Windowing Strategies *(8 min)*

- **Tumbling**: fixed, non-overlapping ($[0, 1), [1, 2)$).
- **Hopping/Sliding**: fixed, overlapping (size, slide).
- **Session**: data-driven gaps, per key.
- **Global**: unbounded with triggers (e.g., count-based).

# Triggers & Accumulation *(7 min)*

- **Triggers**: when to emit (on watermark, processing time, count, custom).
- **Accumulation**: discard, accumulate, or accumulate+retract.
- Re-emit updates as late data refines results.

# Late Data Handling *(5 min)*

- **Allowed Lateness**: accept events arriving after watermark by $\Delta$.
- Side outputs for too-late events (dead-letter, audit, or reprocess).
- Deduplication keys mitigate duplicates on retries.

# Windowed Aggregation (Pseudocode) *(6 min)*

```
source("purchases")
  .assignTimestamp(event.ts)
  .watermark(event.ts - 2m)
  .keyBy(userId)
  .window(tumbling, size=5m)
  .aggregate(sum(amount))
  .trigger(onWatermark)
  .allowedLateness(1m)
  .sideOutput("late")
  .sink("user_spend_5m")
```

# Stateful Processing *(8 min)*

- Operator state: per-key or global.
- Timers: register callbacks for event/processing time.
- Snapshots/checkpoints persist state for recovery and exactly-once.

# Per-Key State Example *(6 min)*

```
// Rolling unique URLs per user with TTL
source("clicks")
  .assignTimestamp(ts).watermark(ts - 1m)
  .keyBy(userId)
  .process(state.set("urls", TTL=24h)) { e =>
    state.urls.add(e.url)
    emit(size=state.urls.count(), userId=e.userId)
  }
  .sink("unique_urls")
```

# Delivery Semantics *(6 min)*

- **At-most-once**: may drop data, no duplicates.
- **At-least-once**: no data loss, duplicates possible.
- **Exactly-once** (effectively-once): no loss, no duplicates (with idempotence/transactions).

# Exactly-Once Pattern *(6 min)*

- Input: partition+offset or sequence IDs.
- Processing: transactional state snapshots (barriers/checkpoints).
- Output: idempotent/transactional sink with commit on checkpoint.

# Stream–Stream Joins *(8 min)*

- Requires windows + time alignment + per-key state.
- **Inner/Left/Right/Outer** joins over temporal intervals.
- Reordering late events: update/retract results as needed.

# Join Sketch (Pseudocode) *(6 min)*

```
source("orders").assignTimestamp(ts)
  .join(source("payments").assignTimestamp(ts))
  .onKey(orderId)
  .within(window=15m)            // temporal join bound
  .trigger(onWatermark)
  .emit(orderId, status)
  .sink("order_payment_join")
```

# Backpressure & Flow Control *(7 min)*

- When downstream is slower than upstream, buffers fill.
- Strategies: bounded queues, rate limiting, adaptive batching.
- Scale-out hotspots by key partitioning and rebalancing.

# Fault Tolerance *(8 min)*

- Checkpoints + replay from durable logs.
- Exactly-once sinks: two-phase commit or idempotent upserts.
- Stateless vs stateful recovery times and trade-offs.

# Testing Strategies *(6 min)*

- Deterministic test harnesses: feed records with timestamps.
- Golden files for windowed outputs under reordering/latency.
- Property-based tests: idempotence, associativity of combiners.

# Observability *(4 min)*

- Metrics: input/output rates, watermark lag, busy time, backlogs.
- Logs and event samples for debugging late/duplicate paths.
- Traces across source $\rightarrow$ processor $\rightarrow$ sink.

# Cost & Capacity *(4 min)*

- Cardinality drives state size; state drives memory and checkpoint cost.
- Window width and lateness increase storage and compute.
- Right-size partitions and autoscaling policies.

# Exercise 1: Window Choices *(6 min)*

**Scenario:** Rolling user activity dashboard.
**Task:** Pick window type (tumbling/hopping/session) and trigger policy.
**Deliverable:** One-slide justification (latency vs accuracy vs cost).

# Exercise 2: Late Data Plan *(6 min)*

**Scenario:** Mobile telemetry with flaky connectivity.
**Task:** Choose watermark, allowed lateness, and side-output policy.
**Deliverable:** Policy doc: how to reconcile late updates in downstream stores.

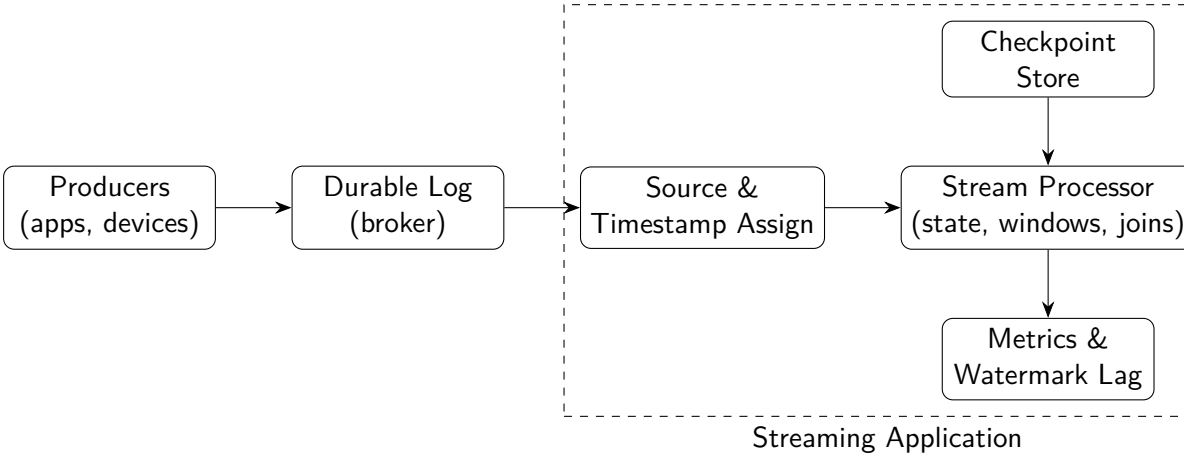
# Exercise 3: Exactly-Once Sketch *(6 min)*

**Scenario:** Deduct credits once per order.
**Task:** Outline idempotent keys, checkpoint cadence, and sink commit flow.
**Deliverable:** Sequence diagram with failure/retry paths.

# Reusable Patterns *(8 min)*

- **Dead Letter Stream**: quarantine malformed or too-late events.
- **Outbox/Inbox**: transactional handoff between services.
- **Upsert Sink**: idempotent writes keyed by natural/business IDs.
- **Rekey/Compaction**: change partitioning without data loss.
- **Side Outputs**: route anomalies without blocking main flow.

# Reference Architecture (Conceptual) *(6 min)*



# Quick Quiz *(6 min)*

1. Why prefer event time over processing time for aggregation?
2. What role do watermarks play?
3. Compare tumbling, hopping, and session windows.
4. What is end-to-end exactly-once and how is it achieved?

# Key Takeaways *(3 min)*

- Treat time as data; design with watermarks and late events in mind.
- Windows + triggers define latency vs accuracy trade-offs.
- State and checkpoints enable correctness under failures.
- Backpressure and idempotence are operational essentials.

# Appendix: Glossary

| Term | Meaning |
|---|---|
| Event Time | Timestamp of occurrence |
| Processing Time | Timestamp of observation |
| Watermark | Lower bound on unseen event time |
| Window | Temporal slice for grouping |
| Trigger | Rule for emitting results |
| Allowed Lateness | Grace period for late events |
| State | Persistent operator memory |
| Checkpoint | Consistent snapshot for recovery |
| Backpressure | Slower downstream throttles upstream |

# Appendix: Timing Plan (90–120 min)

| Segment | Minutes |
|---|---|
| Why Streaming | 10 |
| Time & Watermarks | 15 |
| Windows & Triggers | 20 |
| State & Guarantees | 20 |
| Joins & Backpressure | 15 |
| Testing/Observability/Cost | 10 |
| Exercises (3) | 18 |
| Quiz/Wrap | 7 |
| Buffer / Q&A | 5–15 |

Thank you!