Custom, Complex Windows at Scale Using Apache Flink

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QCon San Francisco
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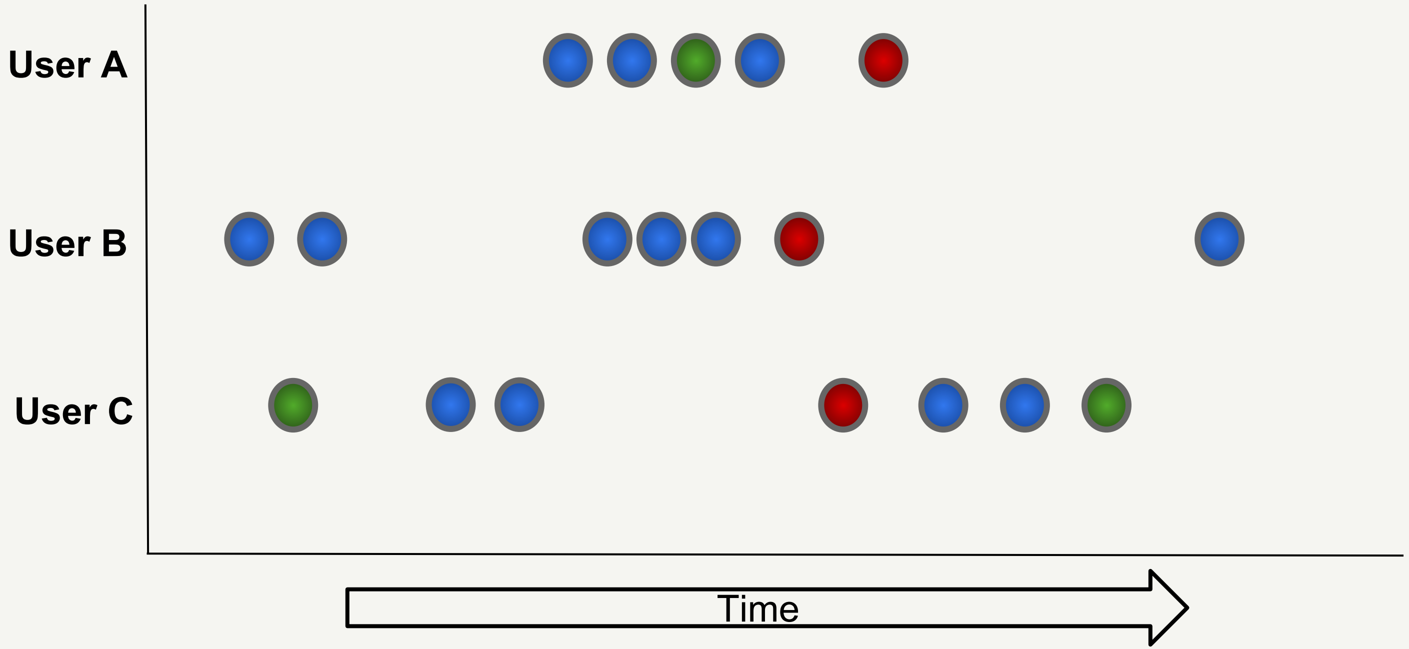
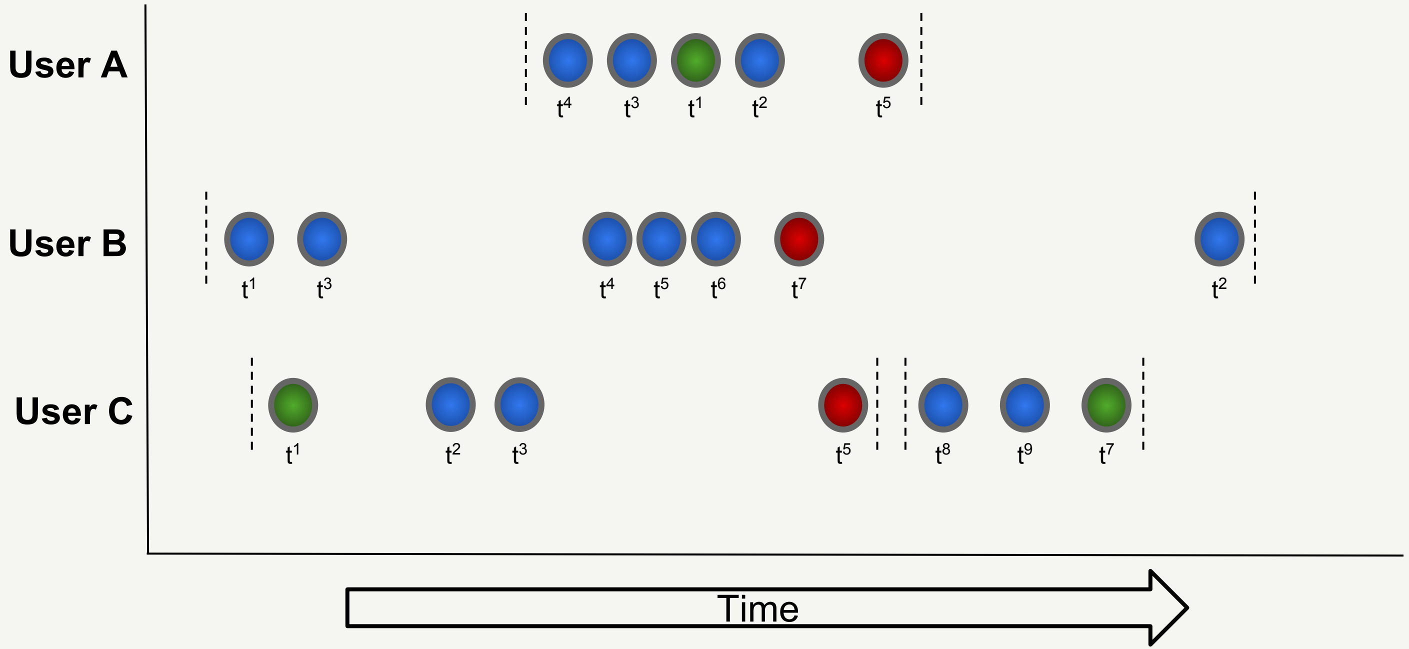
Agenda.

- Motivating Use Cases.
- Window Requirements.
- The Solution (Conceptual).
- Event Processing Flow.
- Apache Flink Window API Walk-Through.
- The Solution (Detail).
- Pitfalls to Watch Out For.
- Alternative Implementations.
- Questions.


User A
User B
User C
Time

Use Case: Most Simple.



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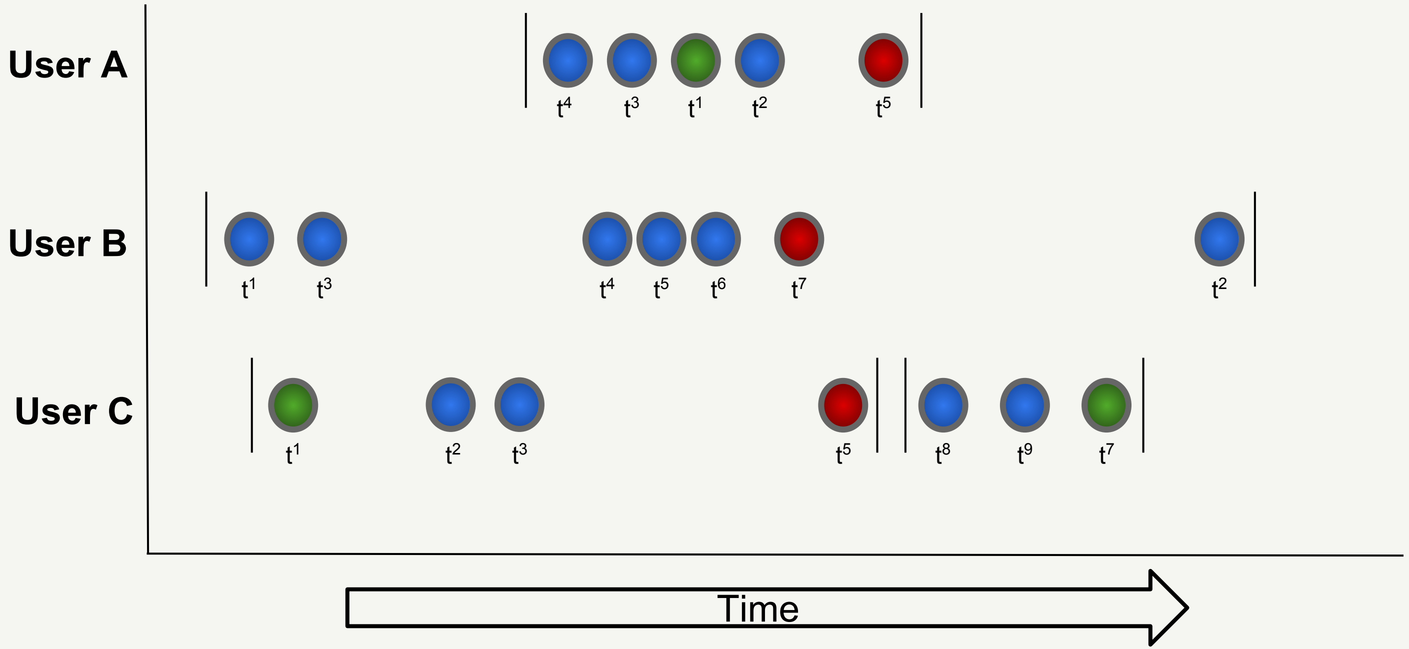
Use Case: Most Simple.



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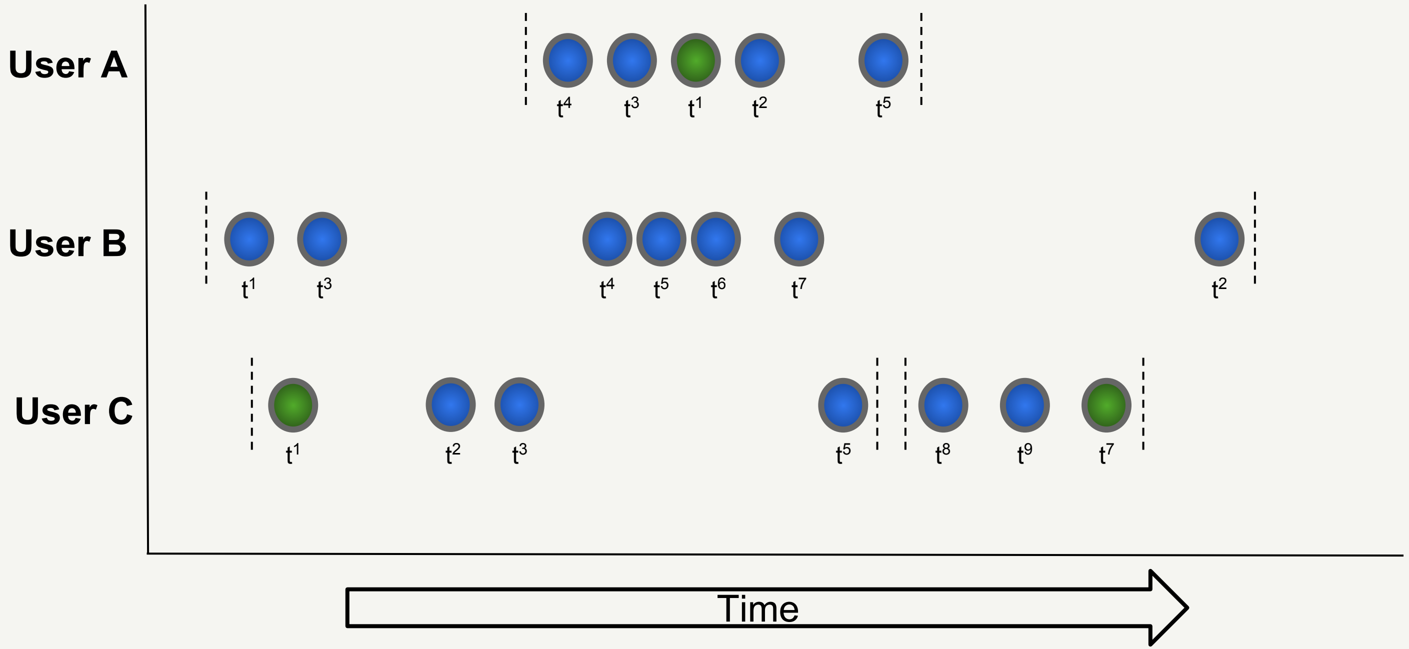
Use Case: More Complex.



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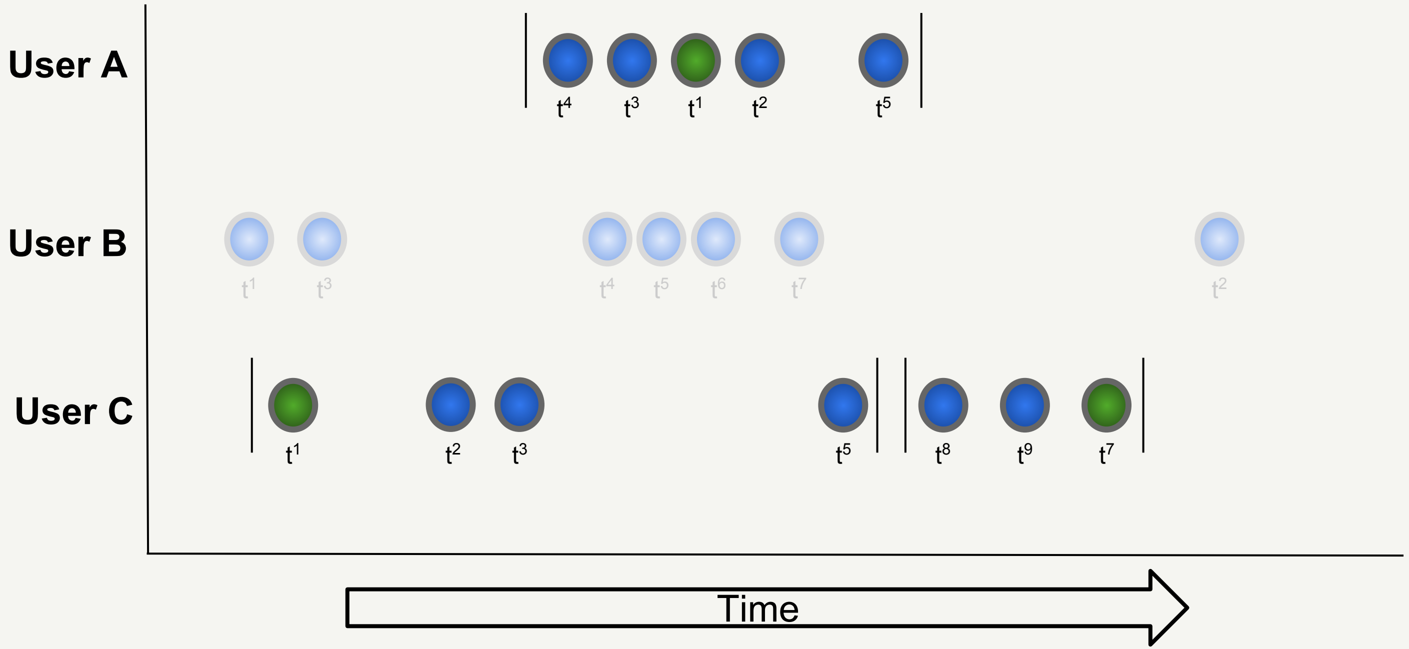
Use Case: More Complex.



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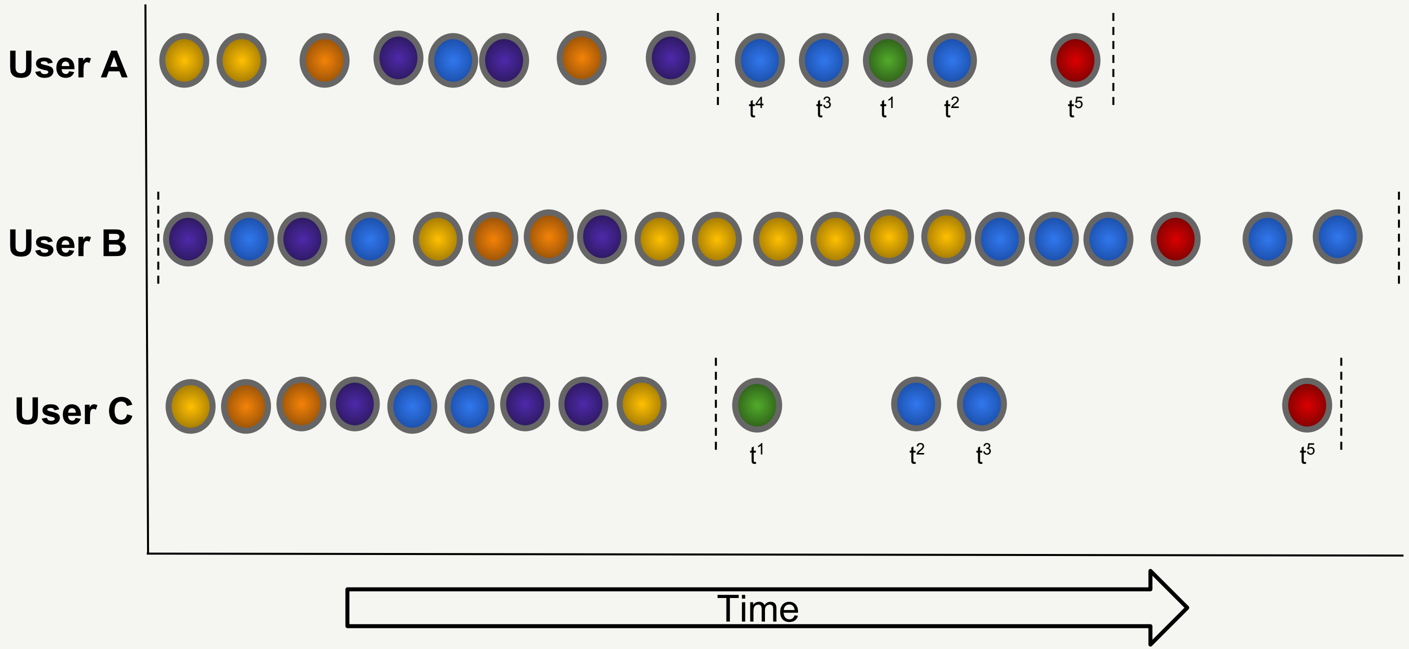
Use Case: Most Complex.



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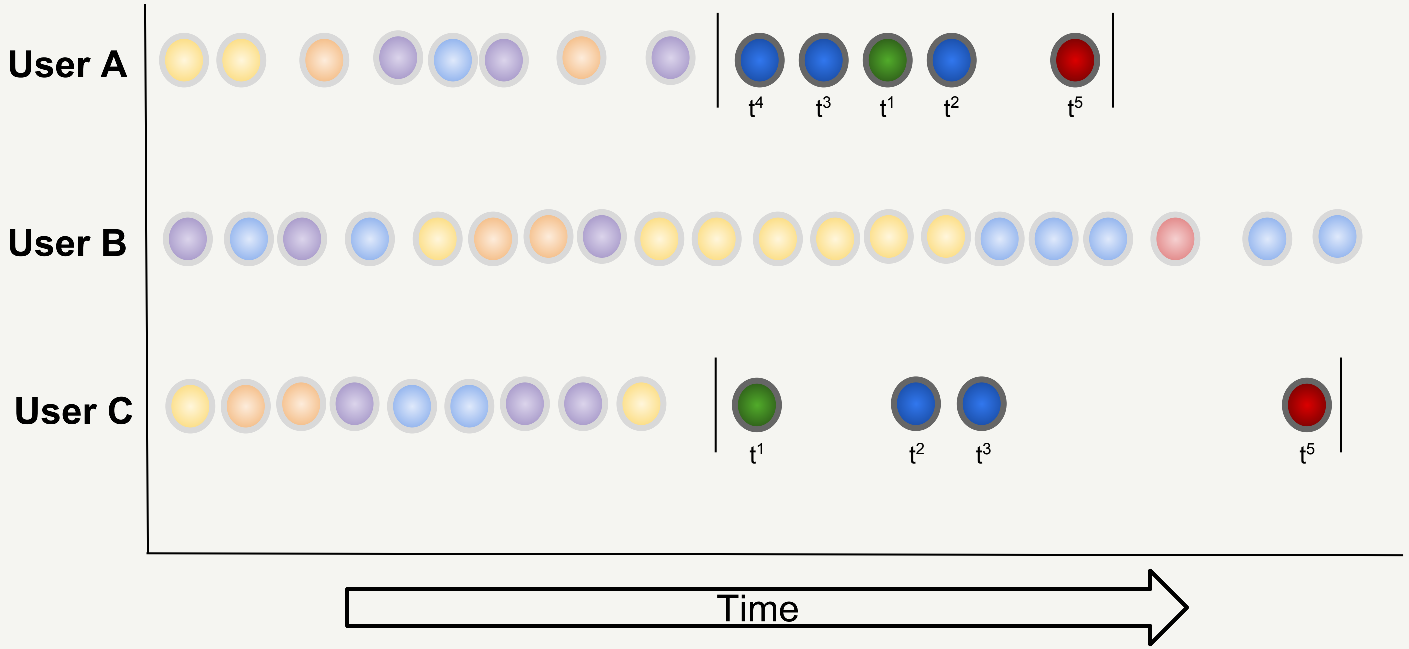
Use Case: Most Complex.



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Targeted Scale.

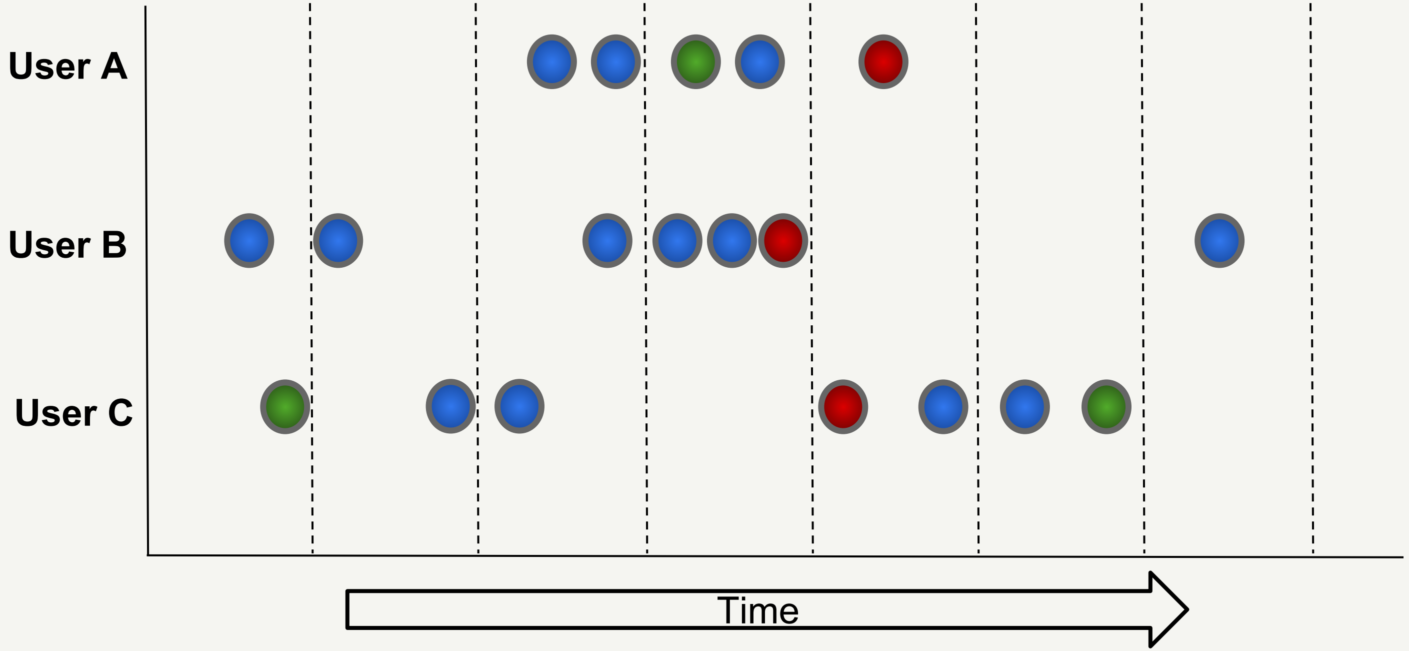
- Events
  - Millions per second
  - 100s billions per day
- Data Flowing In
  - 10s of GiB per second
  - Low (single digit) PiB per day
- State
  - 10s of TiB

Window Requirements.

- Unaligned windows
- Bounded by event type
- Handle out of order events
- Emit early results
- Capture relevant events; ignore the rest

Can we use a standard window type?

Tumbling Window?



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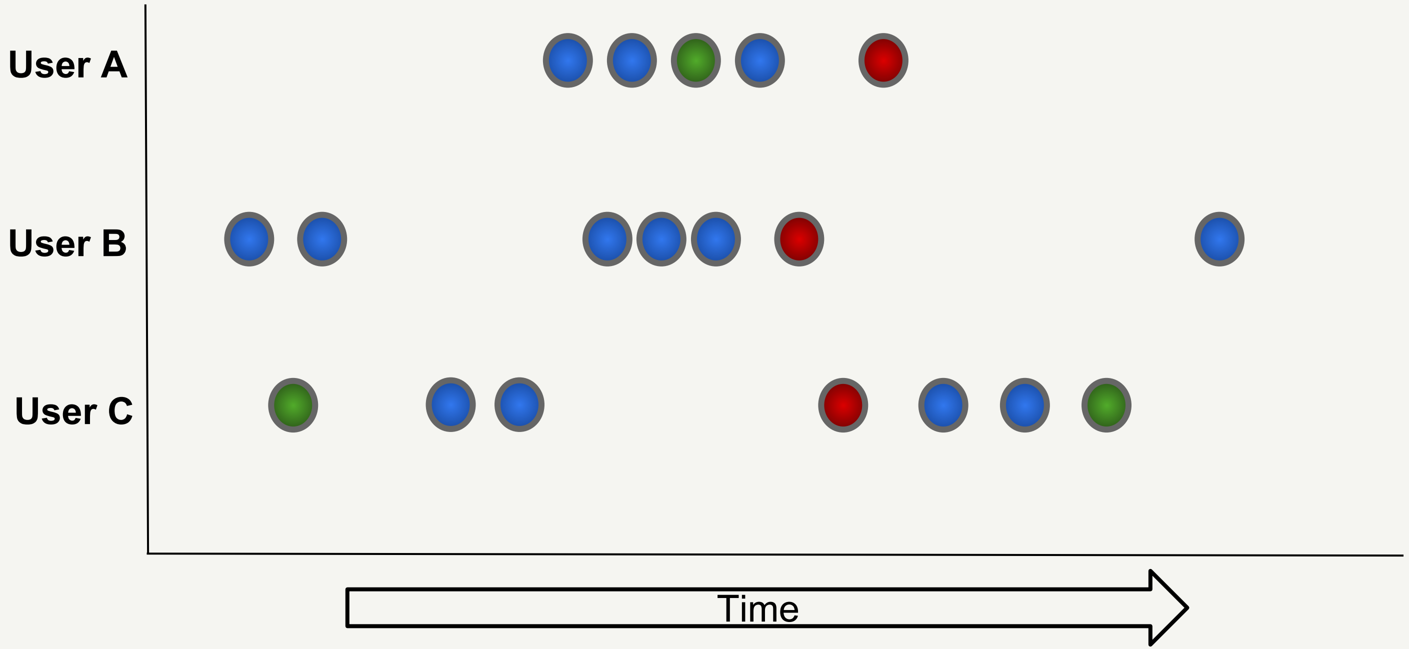
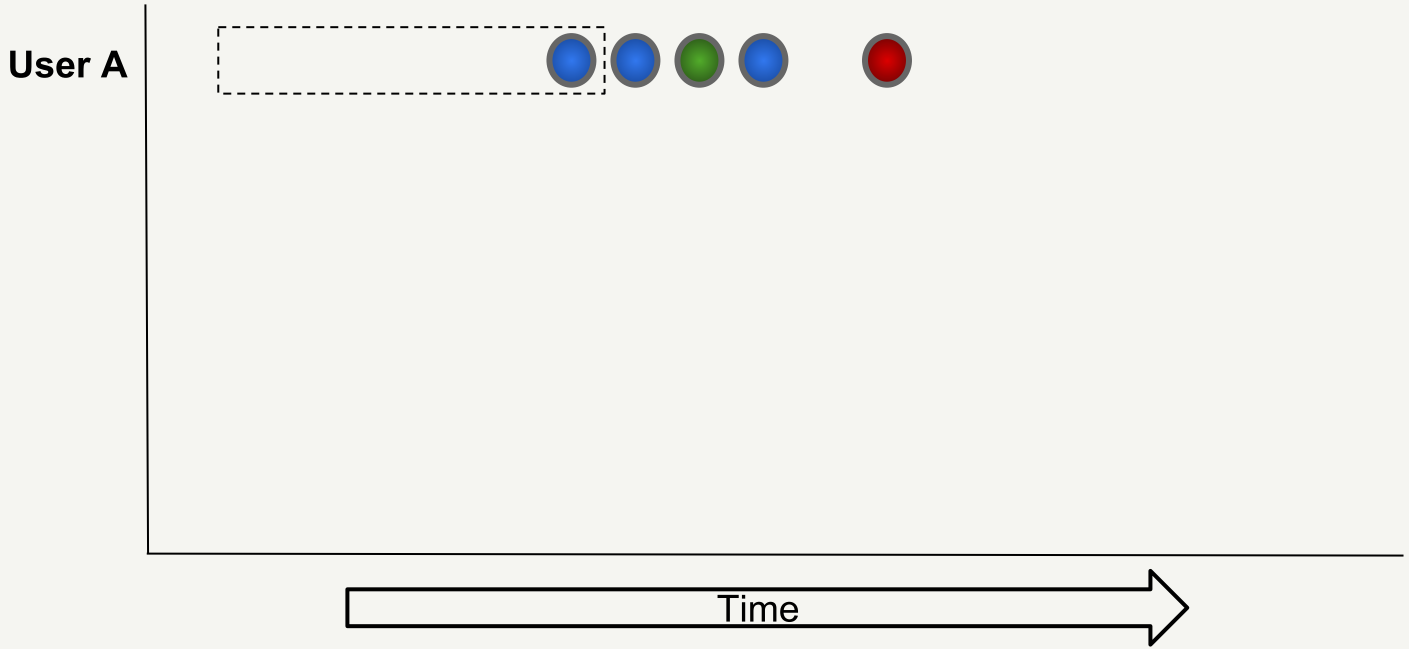
Sliding Window?



Sliding Window?



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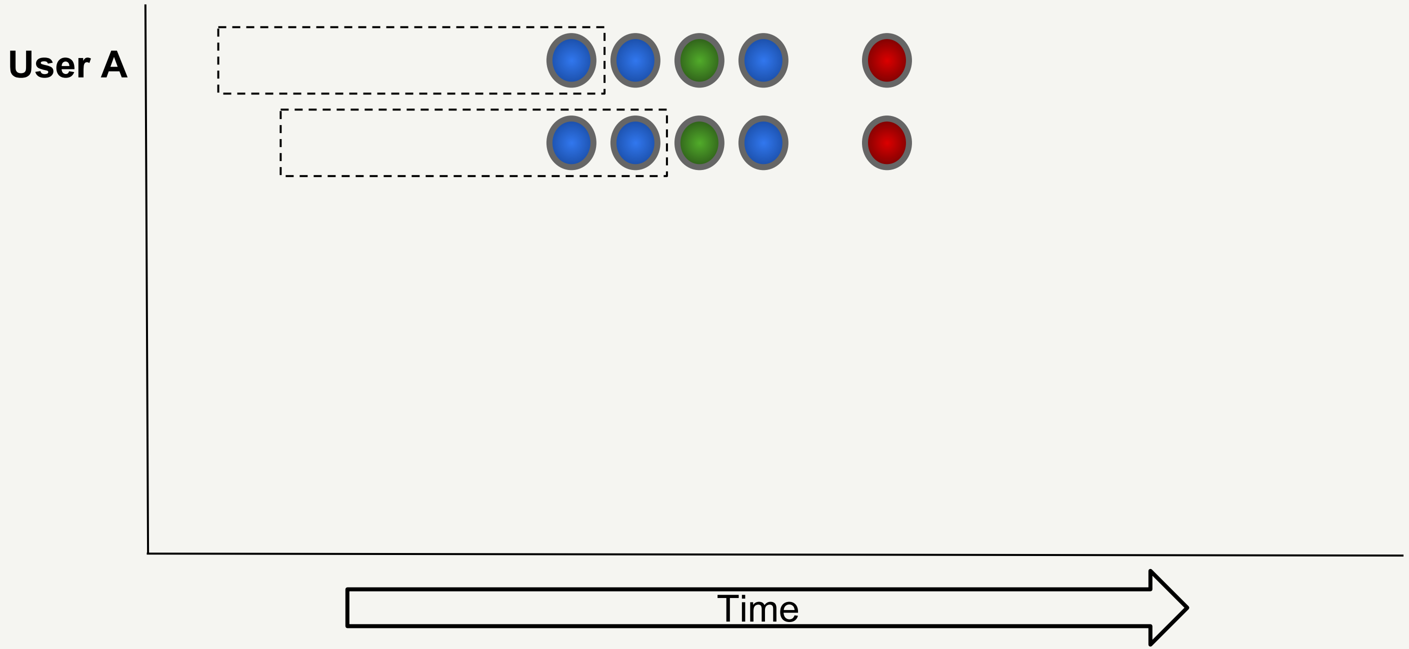
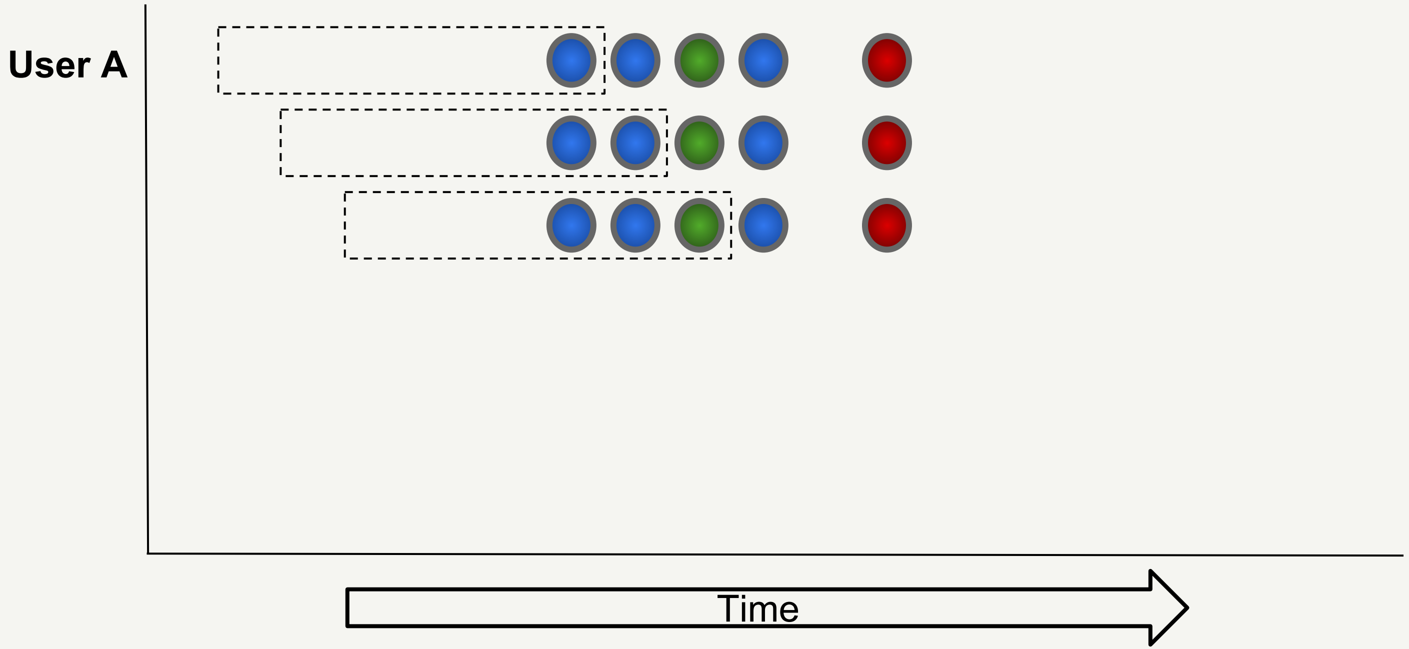
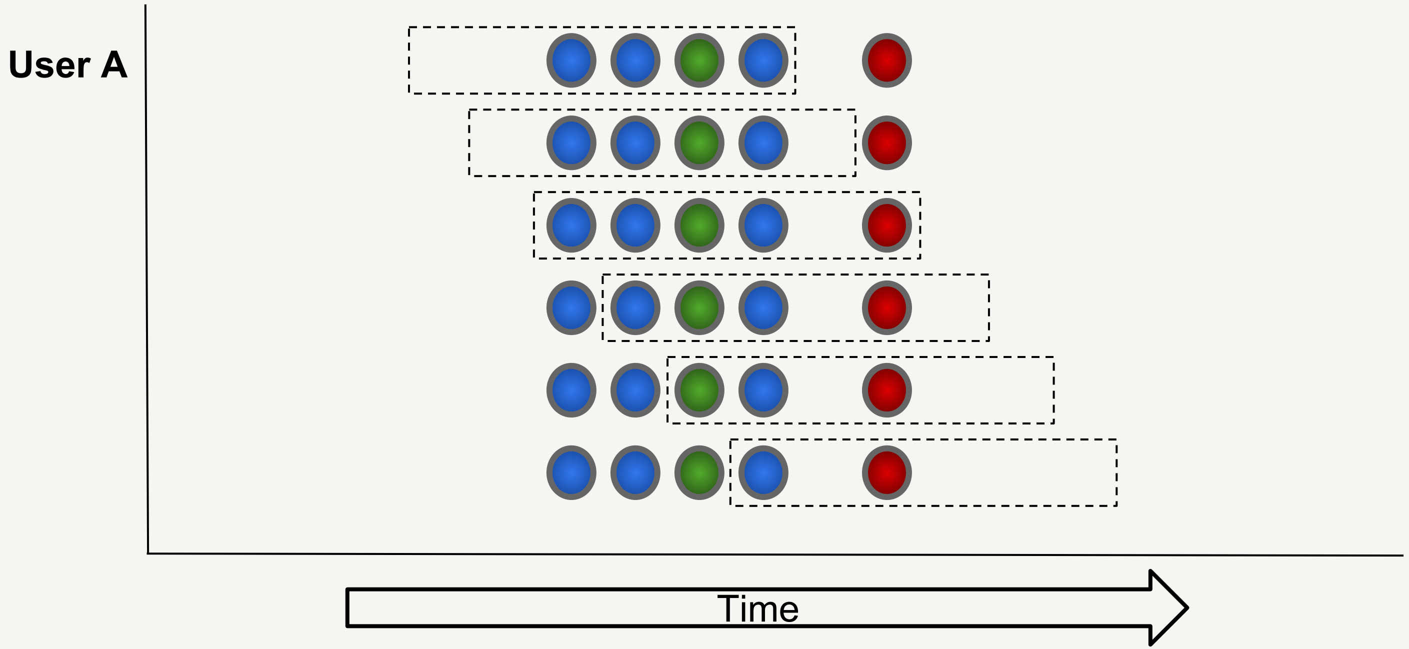
Sliding Window?



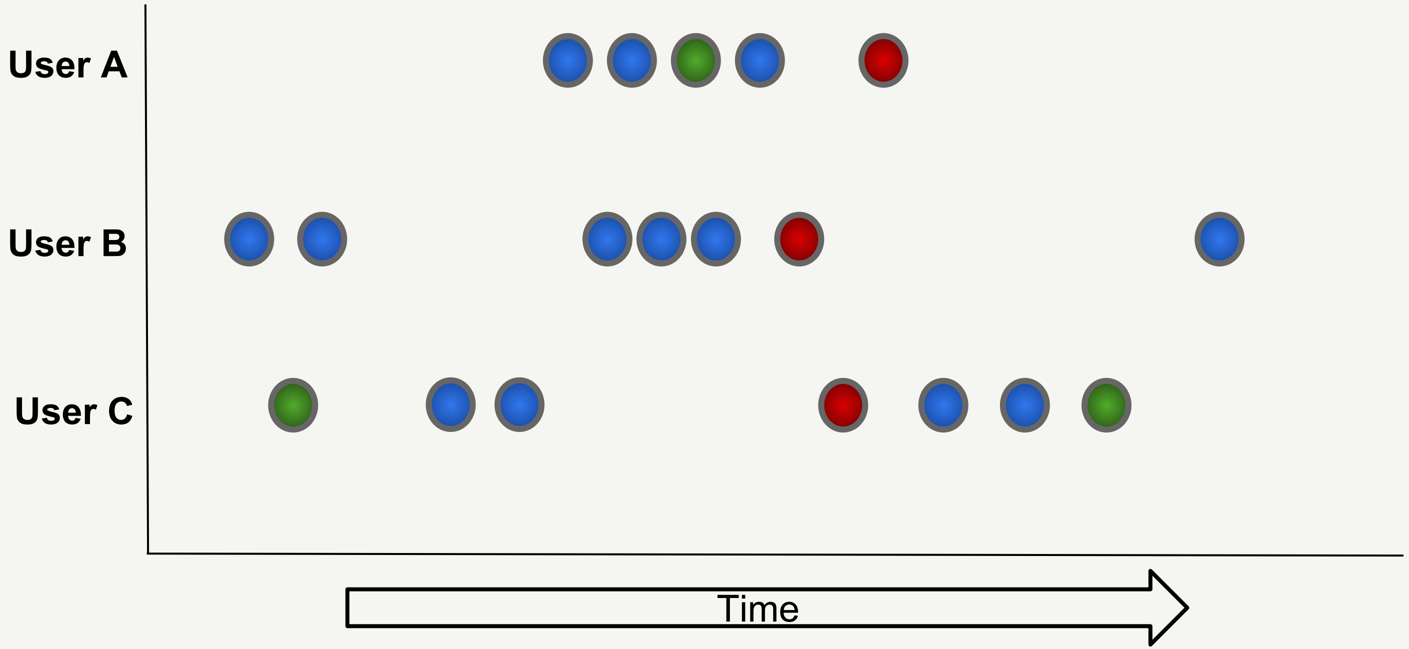
Sliding Window?



Sliding Window?



Apache Beam Session Window?



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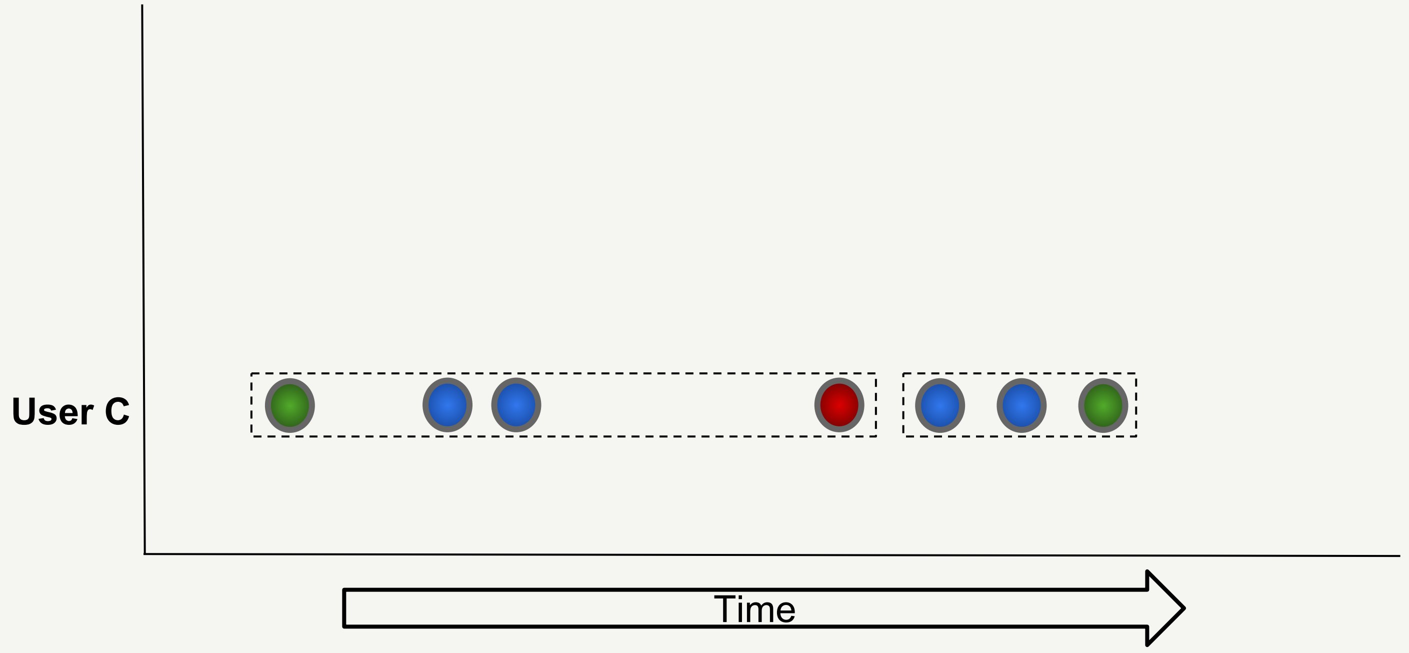
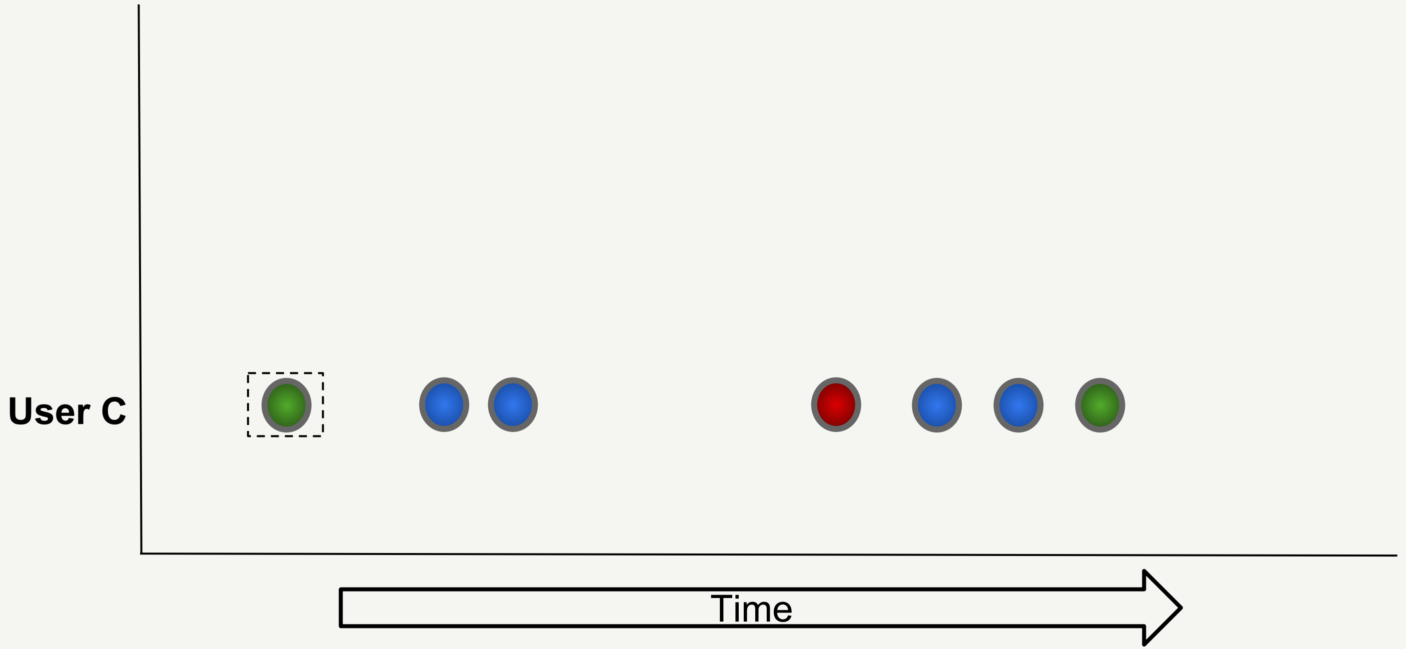
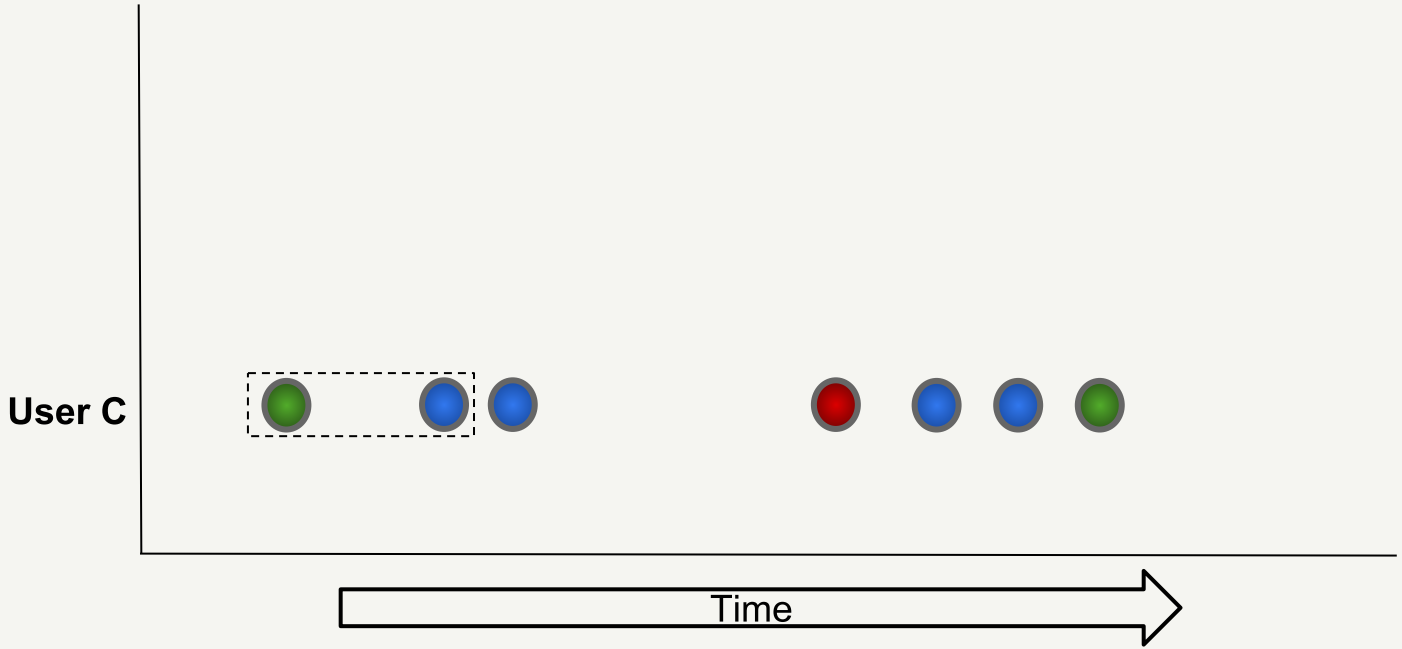
Apache Beam Session Window?



Apache Beam Session Window?



Apache Beam Session Window?



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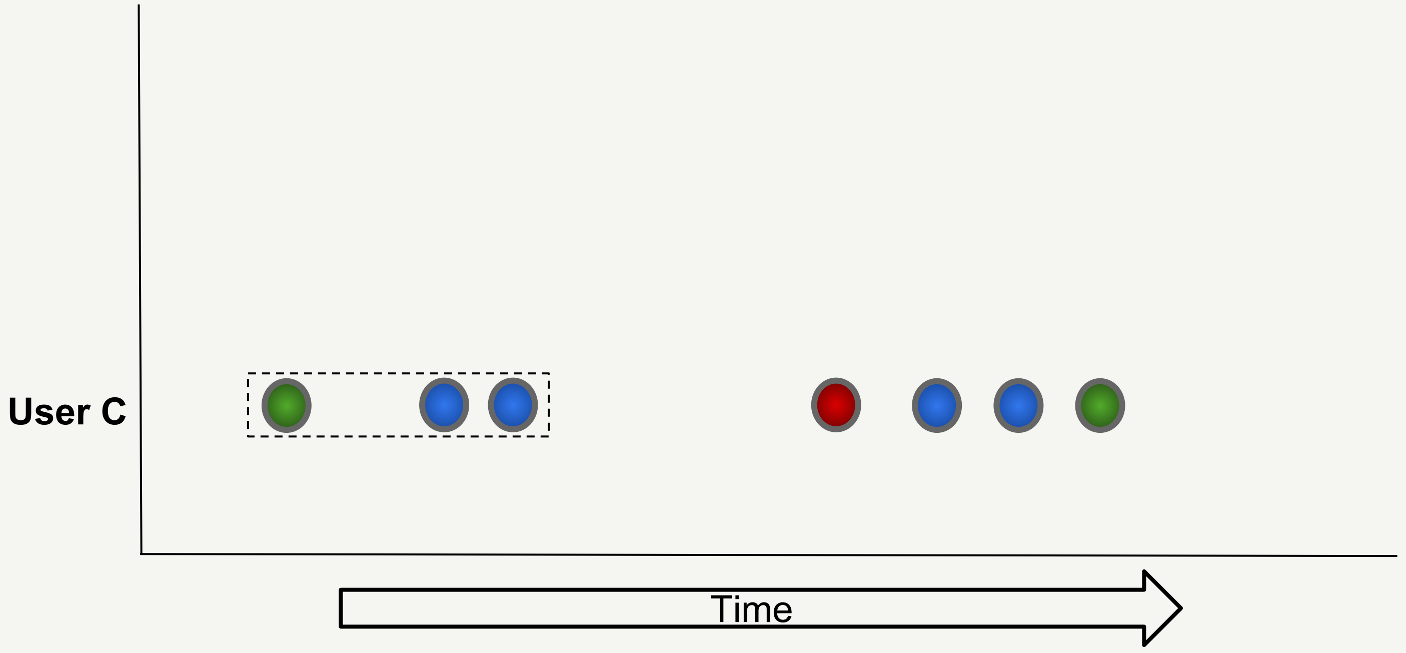

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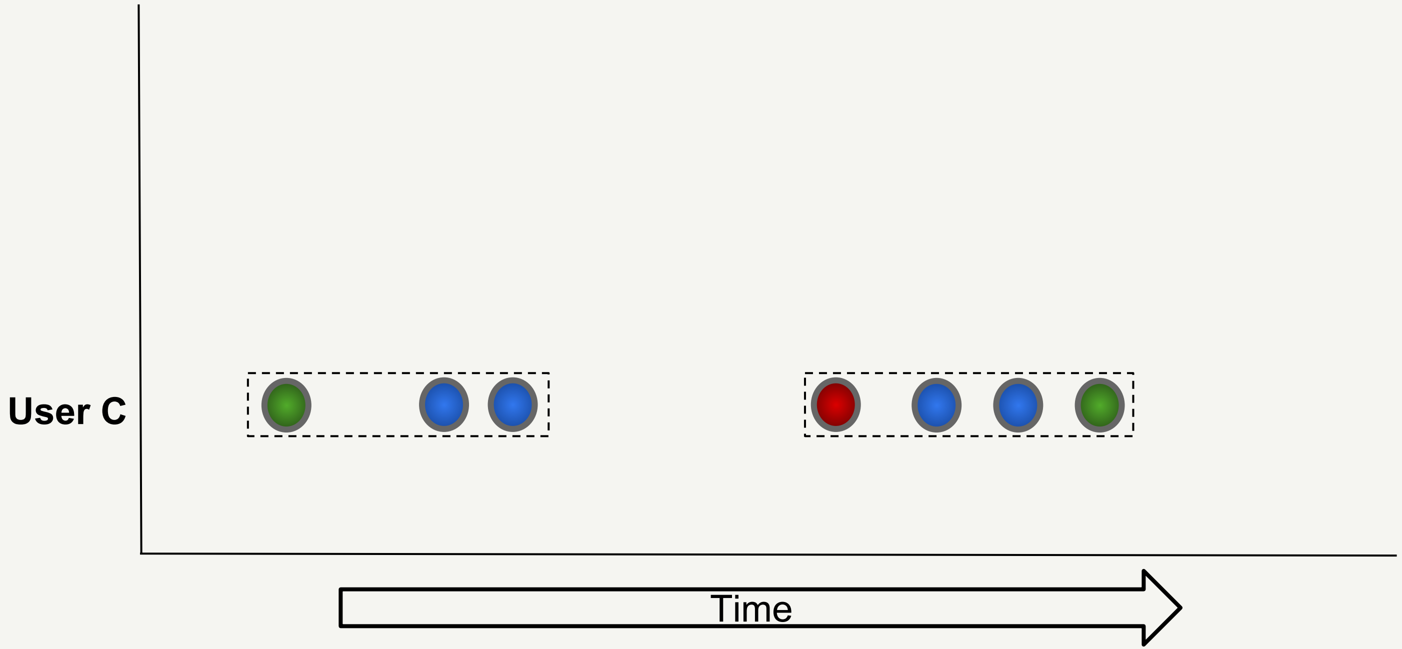

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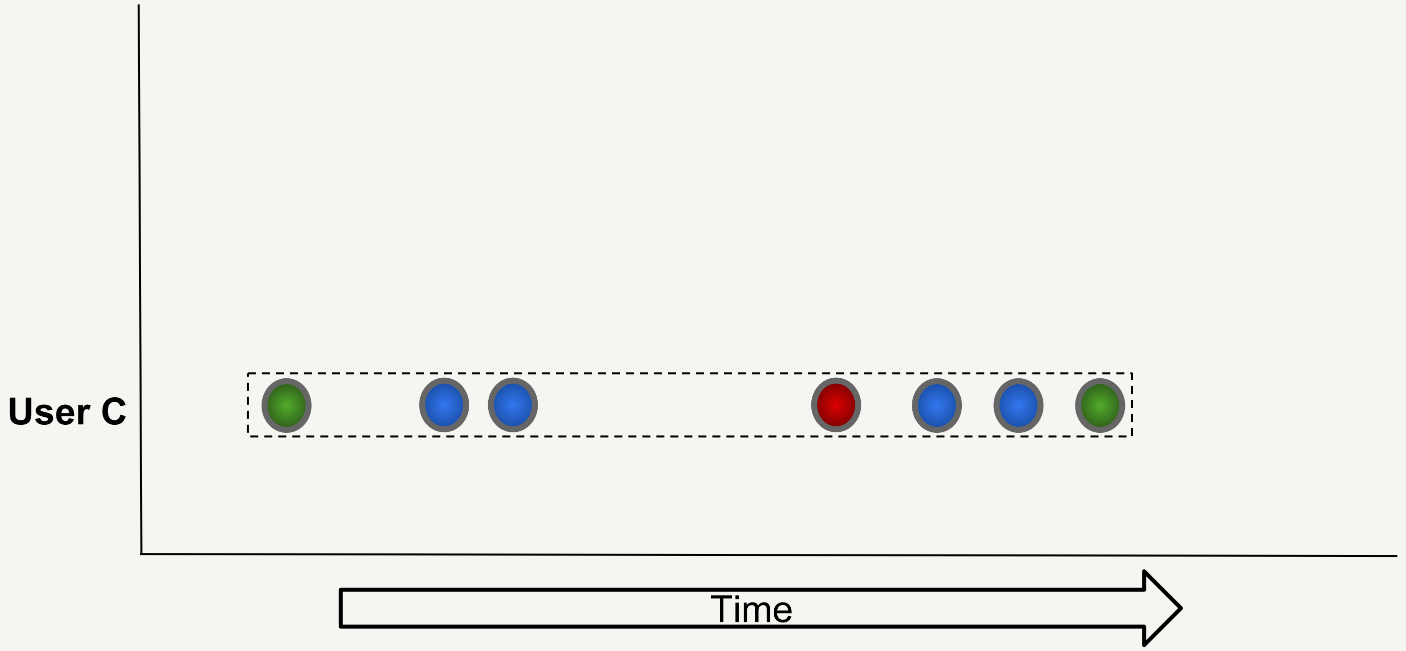


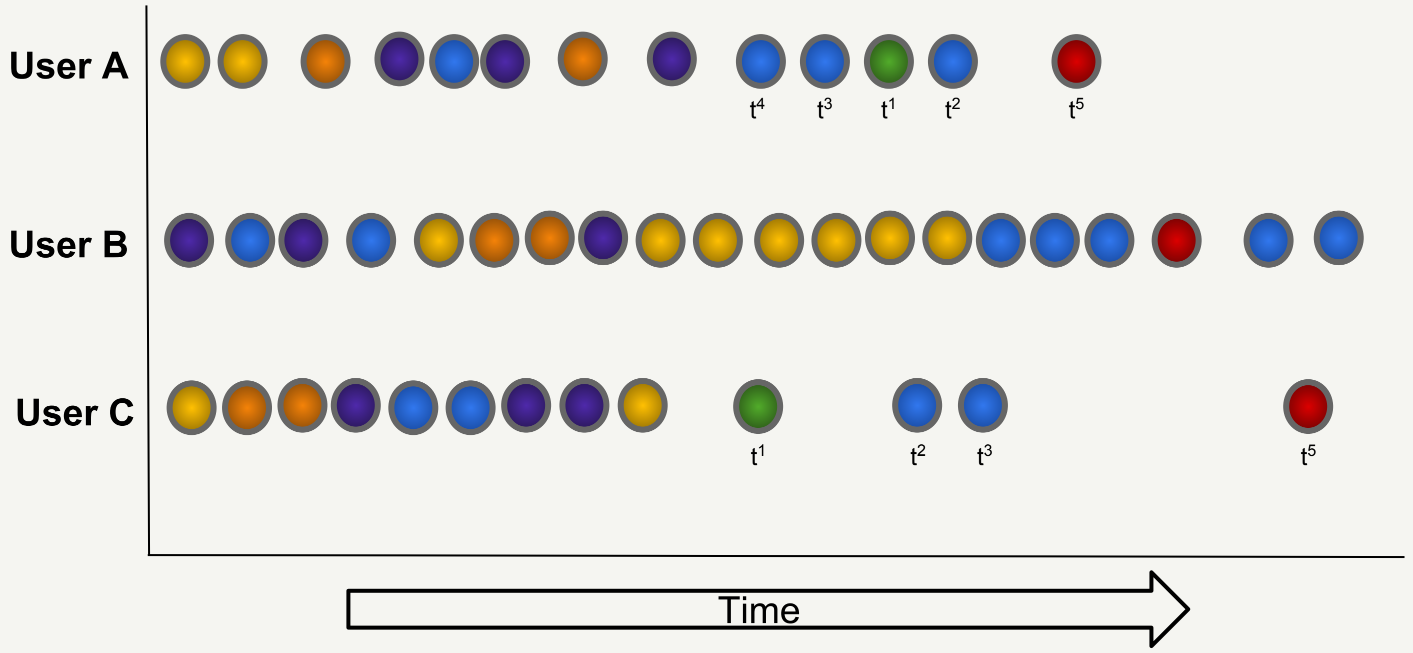
Window Requirements Redux.

- Unaligned windows
- Bounded by event type
- Handle out of order events
- Emit early results
- Capture relevant events; ignore the rest

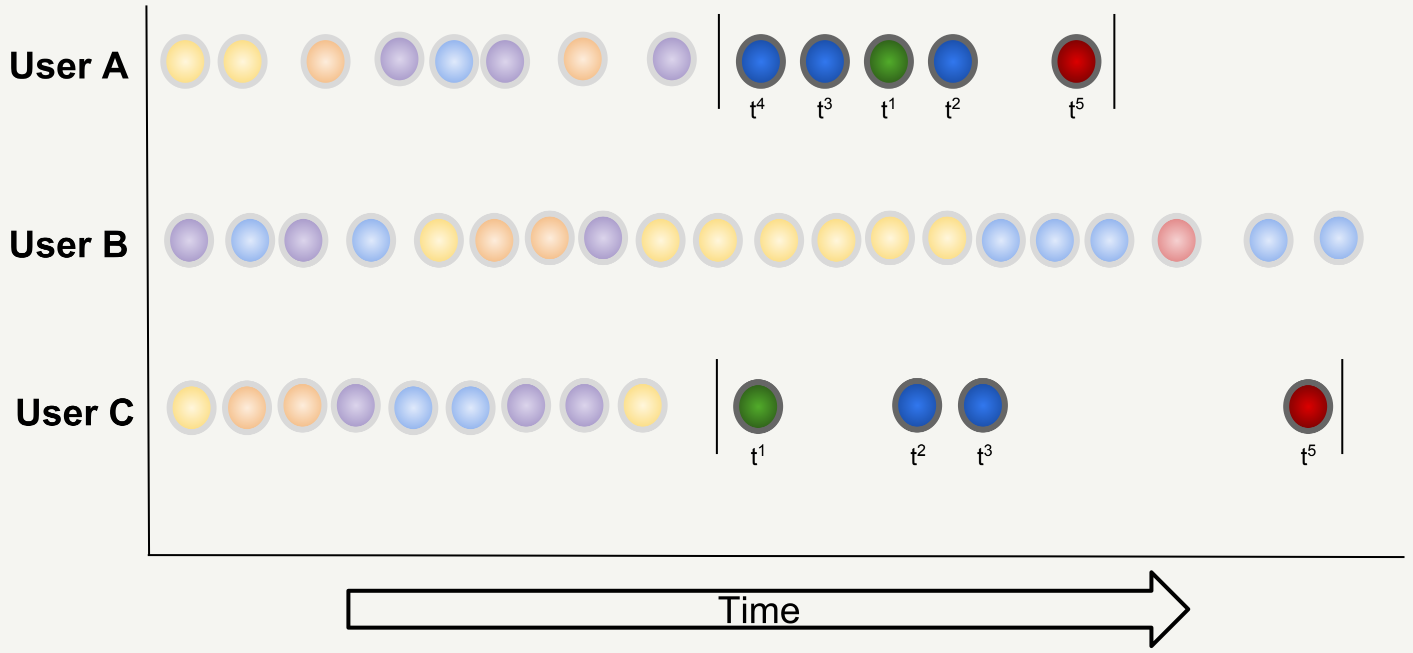
The solution

at 10,000 feet.

The Solution (Conceptual).



The Solution (Conceptual).



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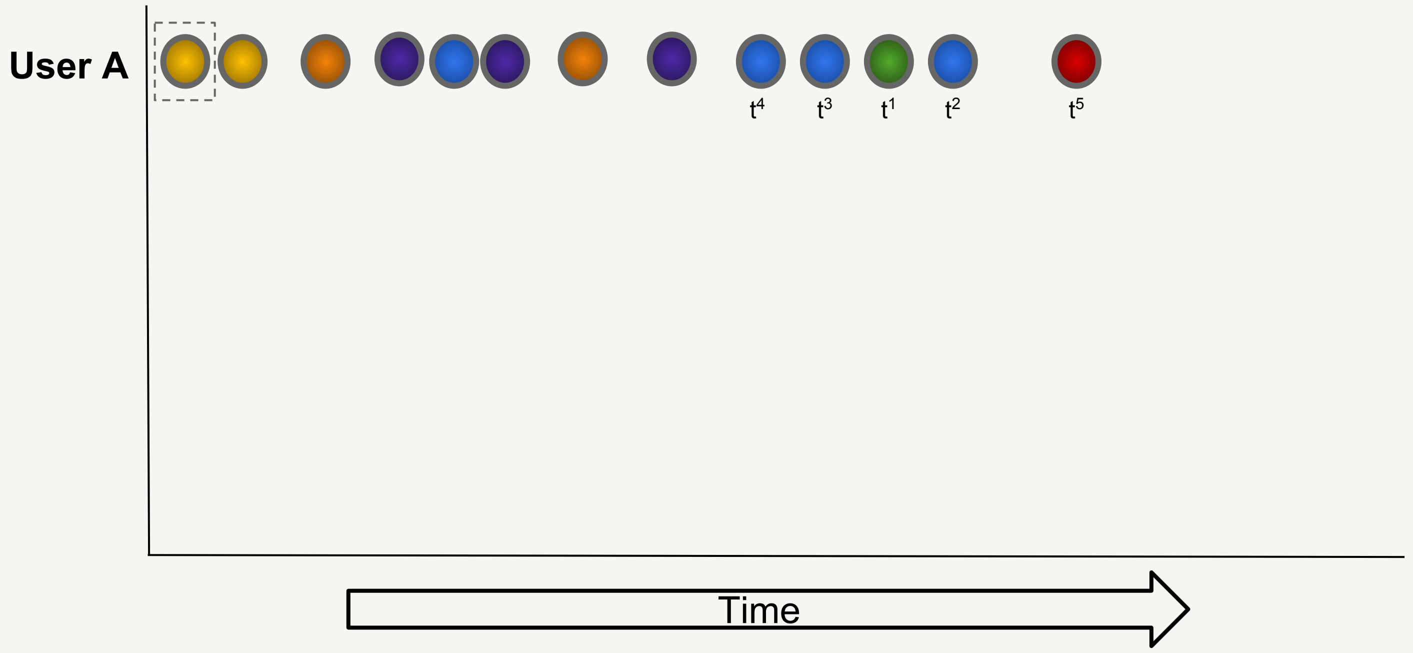
The Solution (Conceptual).



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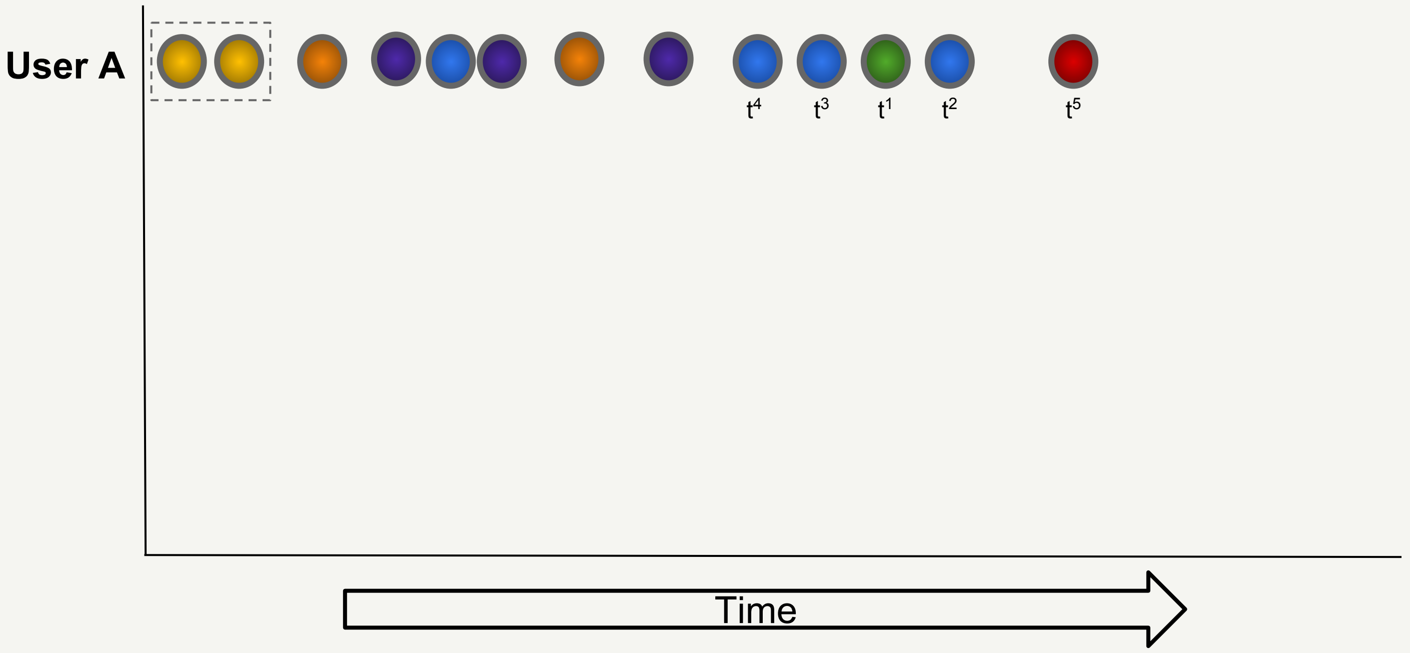

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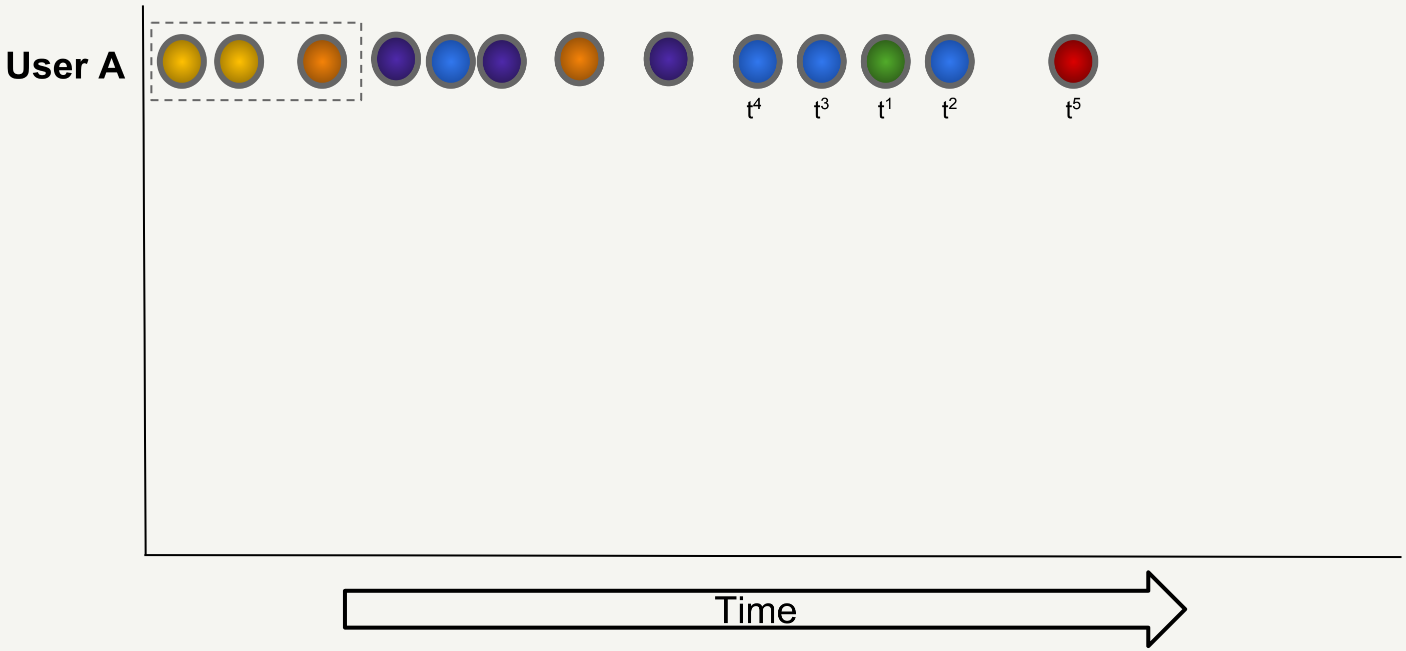
The Solution (Conceptual).



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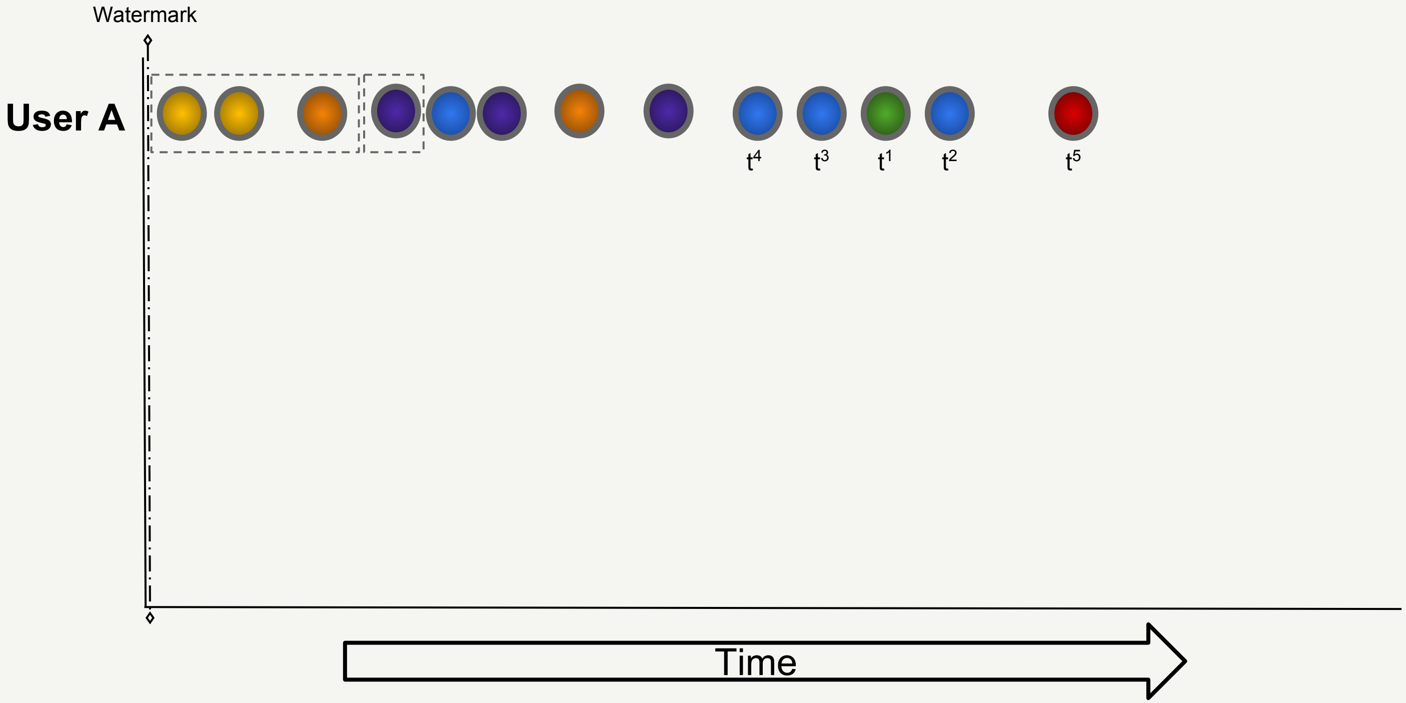

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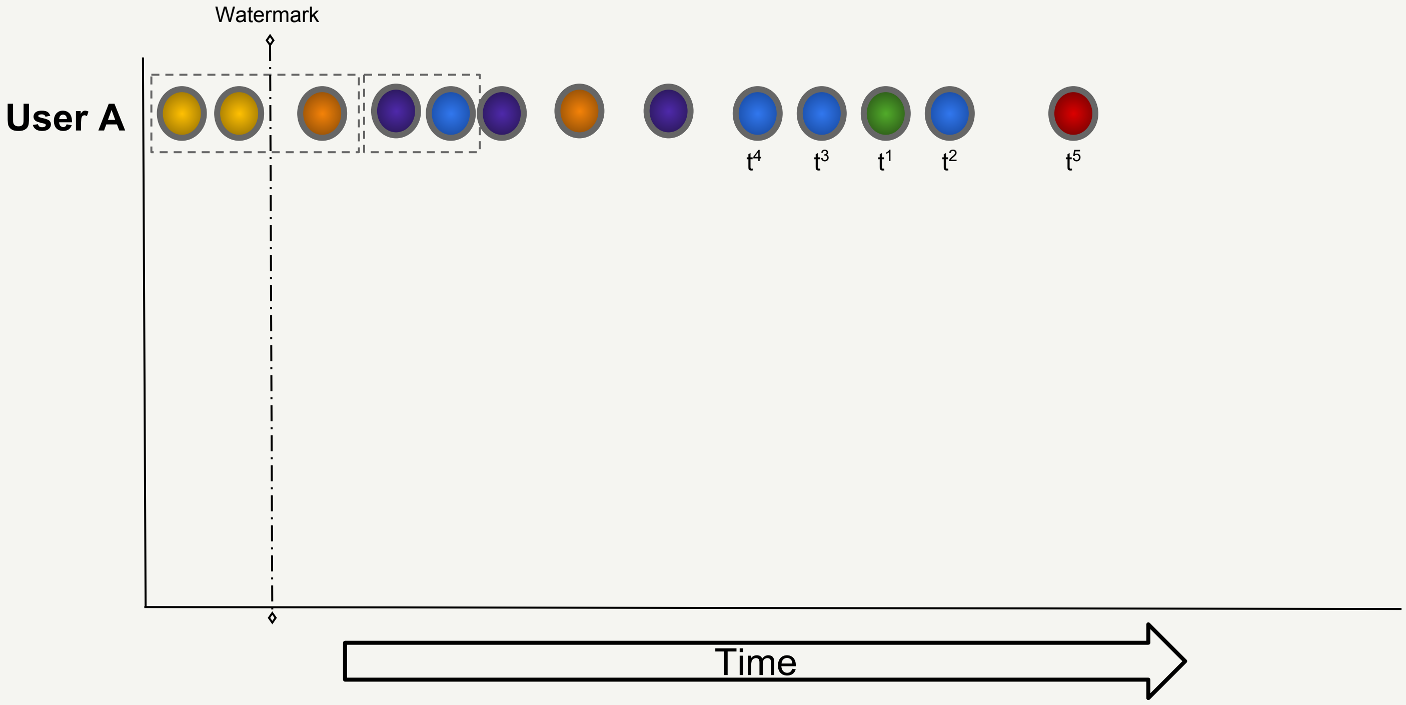

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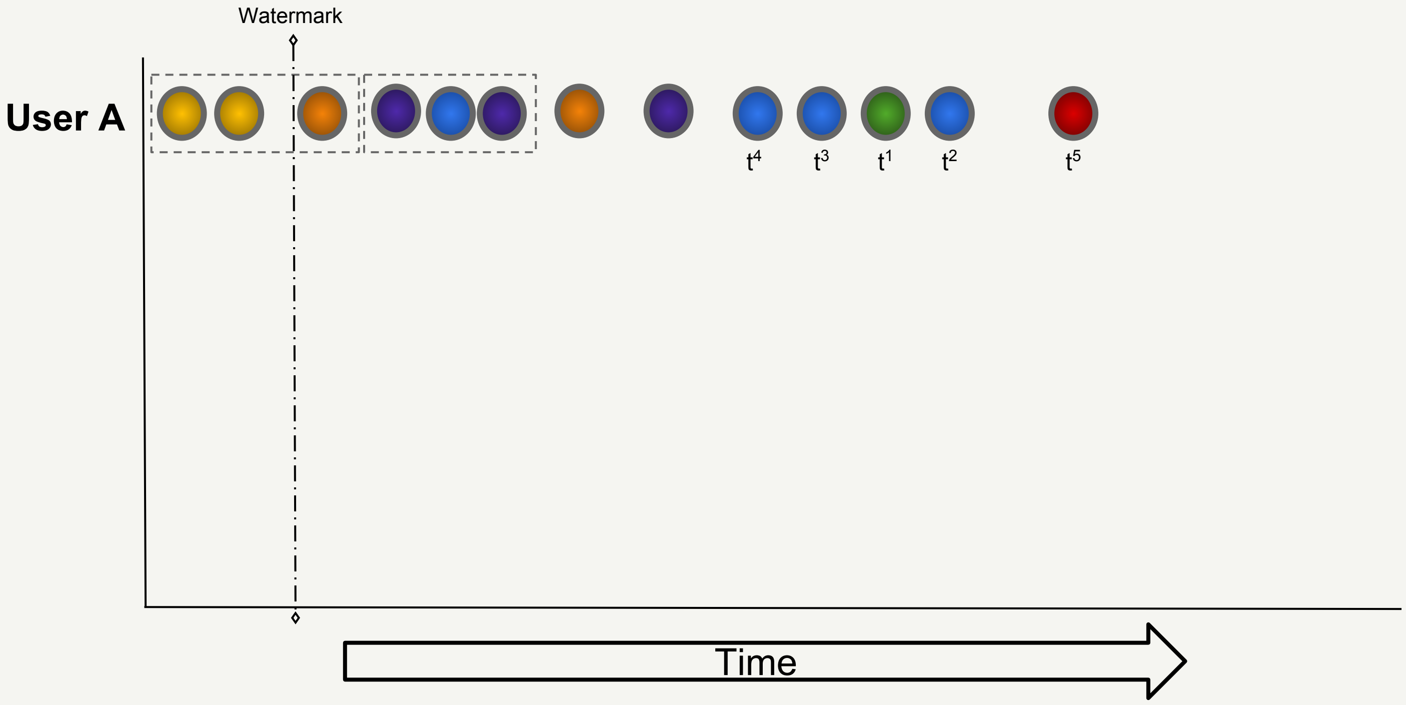

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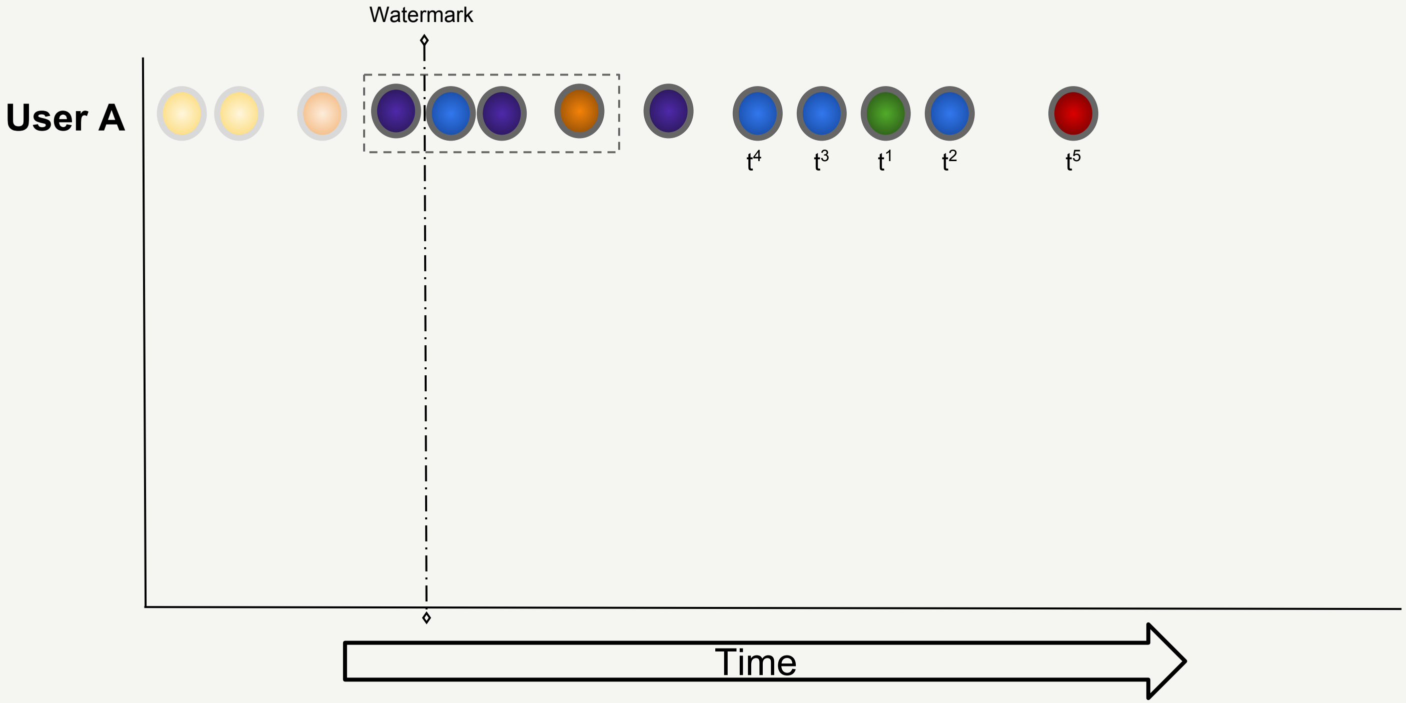

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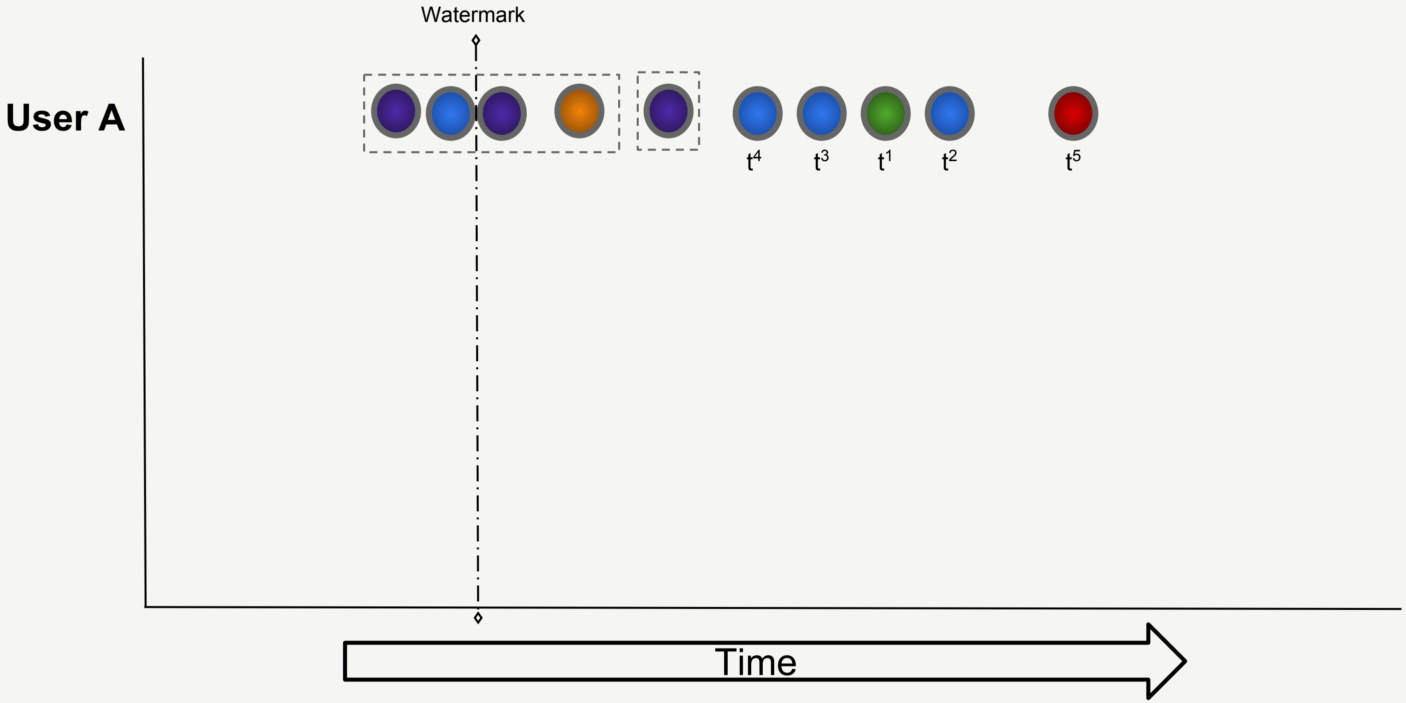

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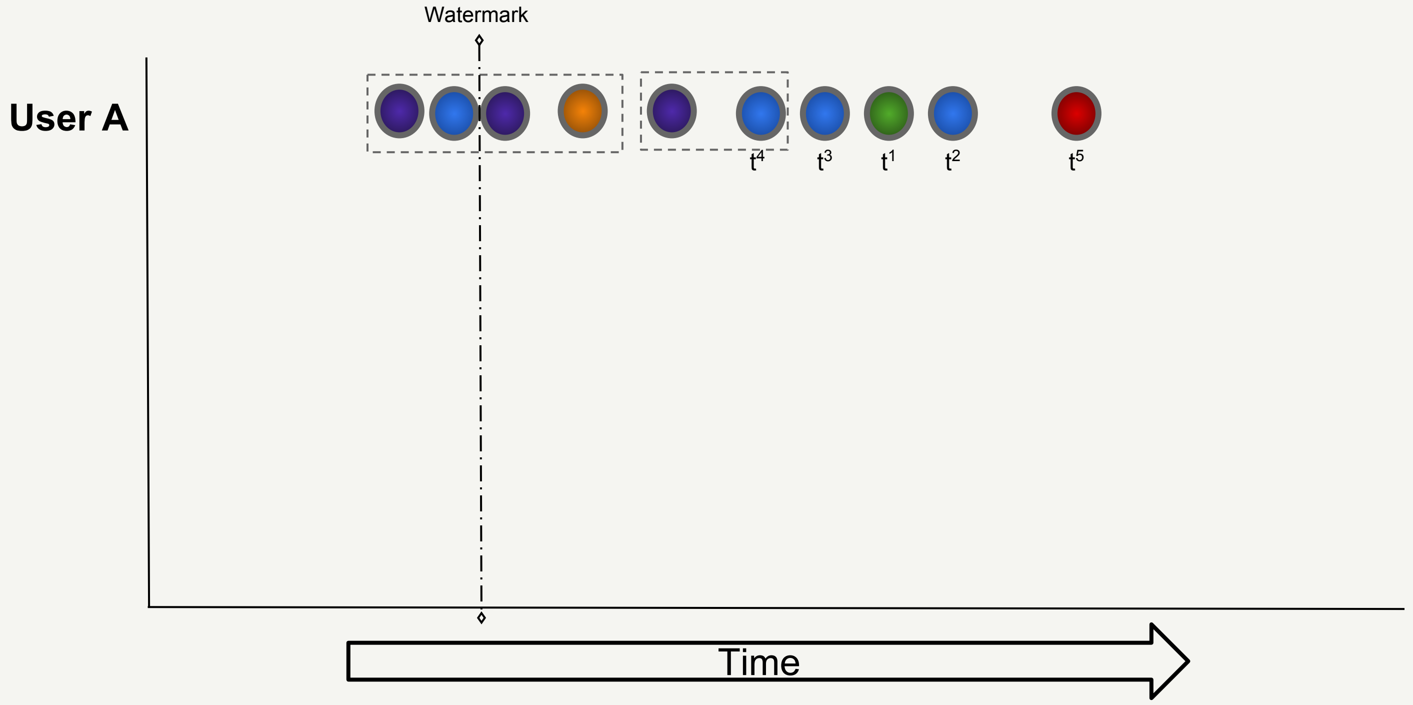

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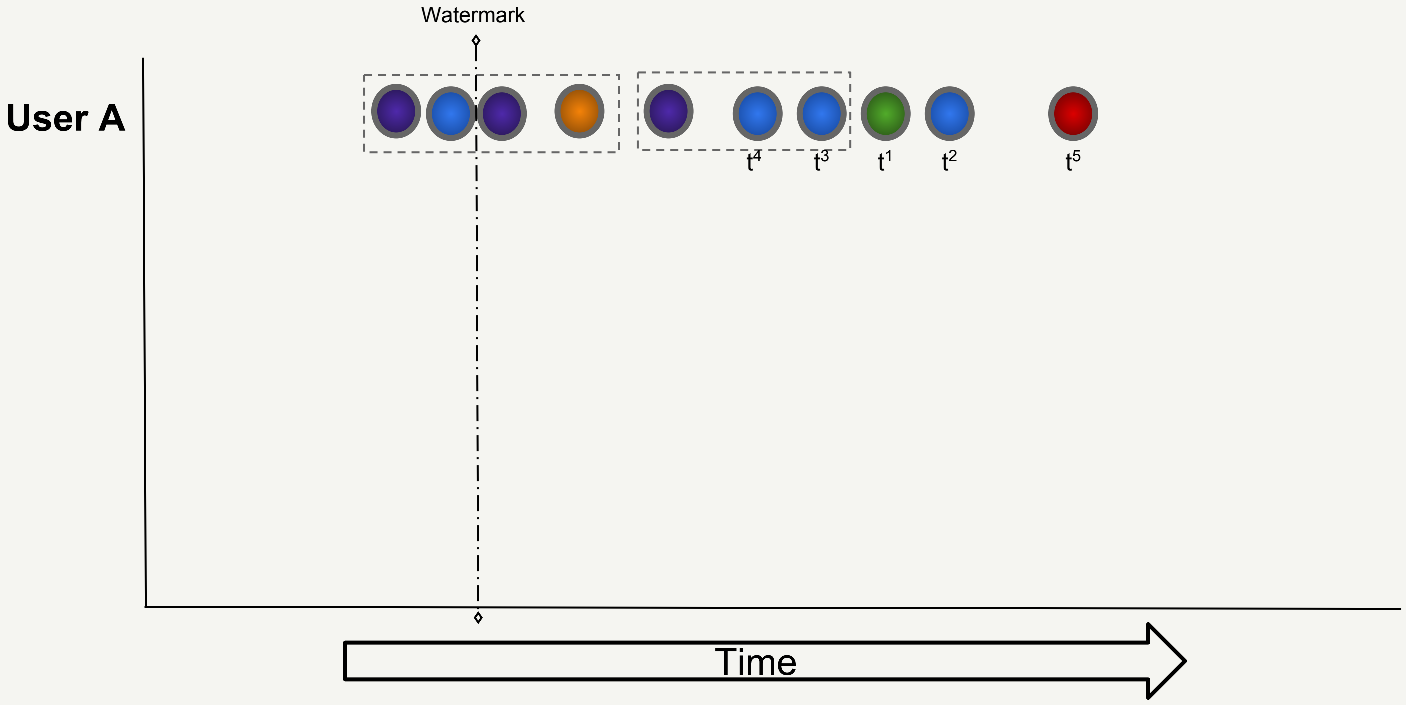

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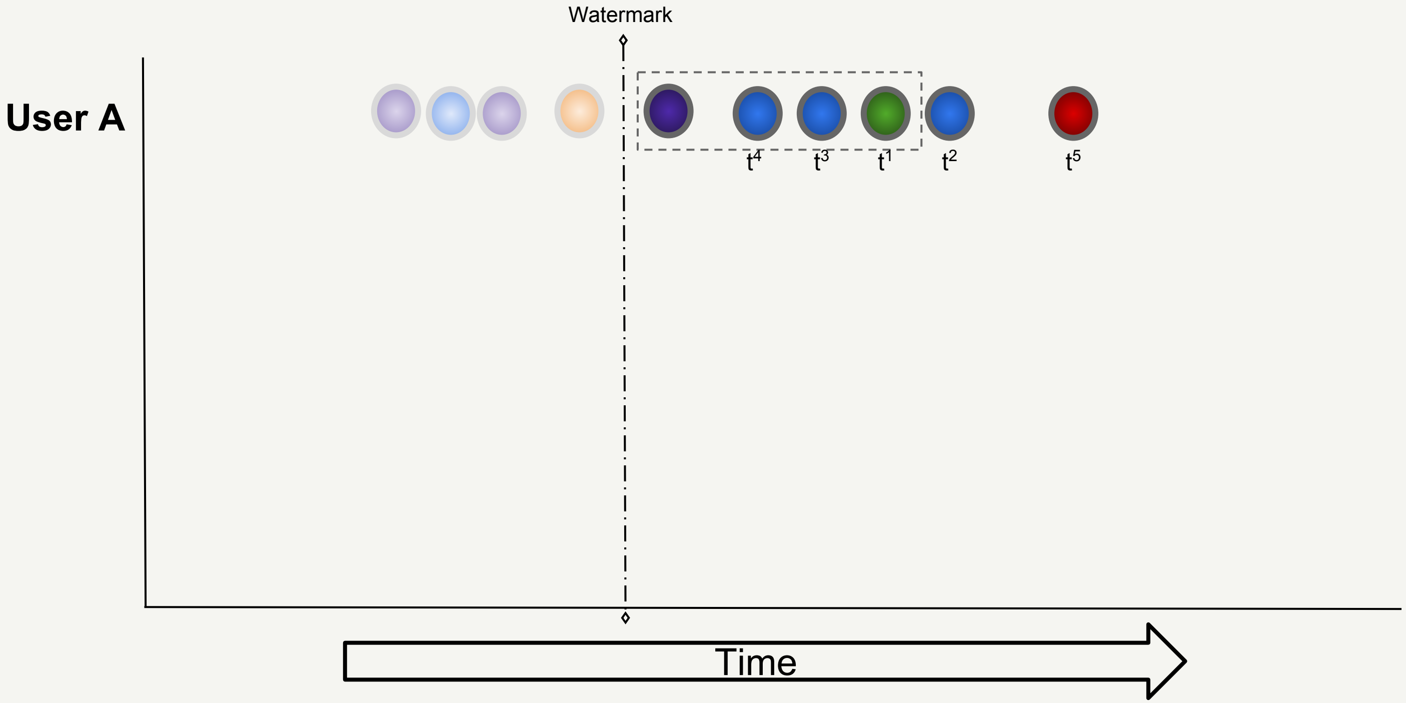

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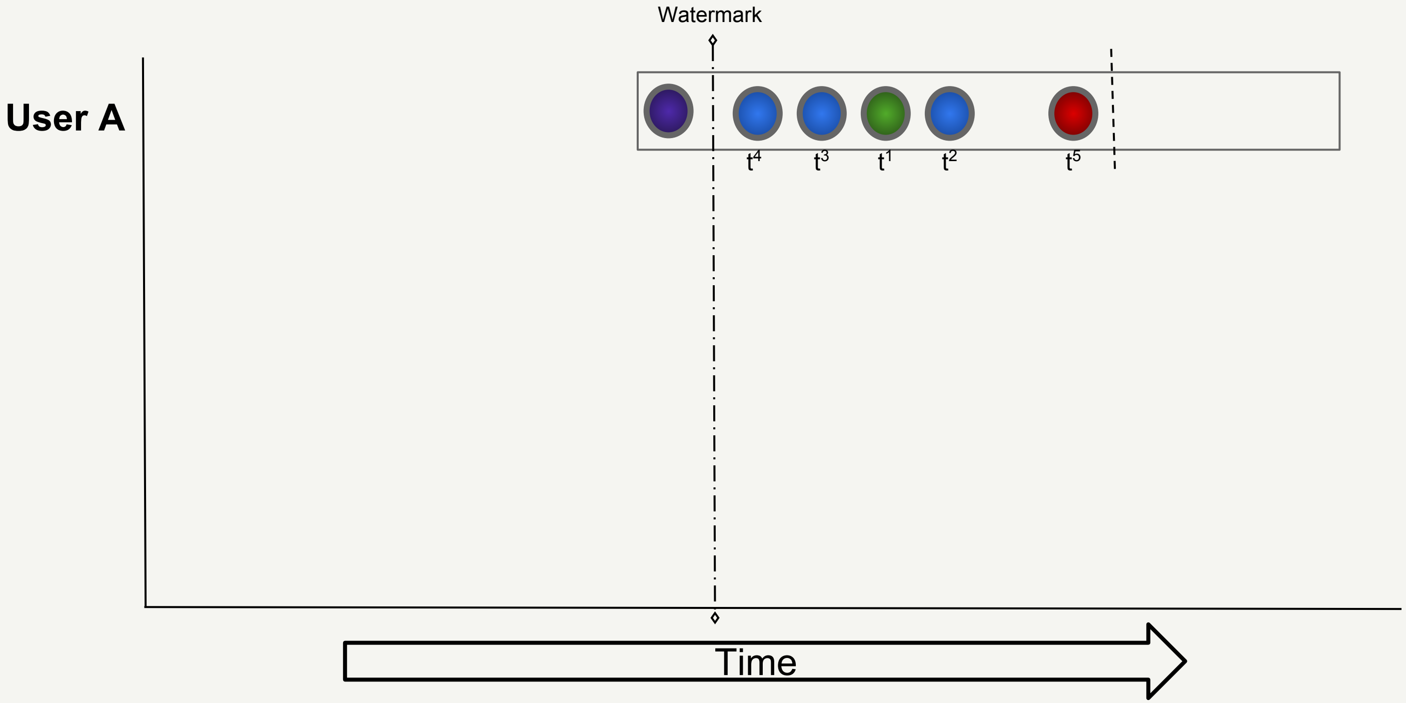

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Event processing flow.

1. Window assigner.

Event processing flow.

1. Window assigner.
   a. Assign Event to Window(s) (`assignWindows`).

Event processing flow.

1. Window assigner.
    a. Assign Event to Window(s) (`assignWindows`).
    b. Merge Windows (`mergeWindows`).

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2. Trigger Handlers.

Event processing flow.

1. Window assigner.
    a. Assign Event to Window(s) (`assignWindows`).
    b. Merge Windows (`mergeWindows`).
2. Trigger Handlers.
    a. Element (`onElement`).

Event processing flow.

1. Window assigner.
    a. Assign Event to Window(s) (`assignWindows`).
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2. Trigger Handlers.
    a. Element (`onElement`).
    b. Merge (`onMerge`).

Event processing flow.

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    b. Merge (`onMerge`).
3. Trigger Timers.

Event processing flow.

1. Window assigner.
    a. Assign Event to Window(s) (`assignWindows`).
    b. Merge Windows (`mergeWindows`).
2. Trigger Handlers.
    a. Element (`onElement`).
    b. Merge (`onMerge`).
3. Trigger Timers.
    a. Processing Time (`onProcessingTime`).

Event processing flow.

1. Window assigner.
    a. Assign Event to Window(s) (`assignWindows`).
    b. Merge Windows (`mergeWindows`).
2. Trigger Handlers.
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    b. Merge (`onMerge`).
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    a. Processing Time (`onProcessingTime`).
    b. Event Time (`onEventTime`).

Event processing flow.

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    a. Processing Time (`onProcessingTime`).
    b. Event Time (`onEventTime`).
4. Evictor.

Event processing flow.

1. Window assigner.
    a. Assign Event to Window(s) (`assignWindows`).
    b. Merge Windows (`mergeWindows`).
2. Trigger Handlers.
    a. Element (`onElement`).
    b. Merge (`onMerge`).
3. Trigger Timers.
    a. Processing Time (`onProcessingTime`).
    b. Event Time (`onEventTime`).
4. Evictor.
    a. Before (`evictBefore`).

Event processing flow.

1. Window assigner.
    a. Assign Event to Window(s) (`assignWindows`).
    b. Merge Windows (`mergeWindows`).
2. Trigger Handlers.
    a. Element (`onElement`).
    b. Merge (`onMerge`).
3. Trigger Timers.
    a. Processing Time (`onProcessingTime`).
    b. Event Time (`onEventTime`).
4. Evictor.
    a. Before (`evictBefore`).
    b. Evaluate Window (`WindowFunction#apply`).

Event processing flow.

1. Window assigner.
    a. Assign Event to Window(s) (`assignWindows`).
    b. Merge Windows (`mergeWindows`).
2. Trigger Handlers.
    a. Element (`onElement`).
    b. Merge (`onMerge`).
3. Trigger Timers.
    a. Processing Time (`onProcessingTime`).
    b. Event Time (`onEventTime`).
4. Evictor.
    a. Before (`evictBefore`).
    b. Evaluate Window (`WindowFunction#apply`).
    c. After (`evictAfter`).

- Motivating Use Cases.
- Window Requirements.
- The Solution (Conceptual).
- Event Processing Flow.
- Apache Flink Window API Walk-Through.
- The Solution in (Detail).
- Pitfalls to Watch Out For.
- Alternative Implementations.
- Questions.

Window API: `Window`.

```
package org.apache.flink.streaming.api.windowing.windows;

public abstract class Window {
      public abstract long maxTimestamp();
}
```

* If you implement Window, you'll need to provide a `TypeSerializer` implementation for it.

Window API: `WindowAssigner`.

```
package org.apache.flink.streaming.api.windowing.assigners;

public abstract class WindowAssigner<T, W extends Window> implements Serializable {
     public abstract Collection<W> assignWindows(T element,
                                                 long timestamp,
                                                 WindowAssignerContext context);
    public abstract Trigger<T, W> getDefaultTrigger(StreamExecutionEnvironment env);
    public abstract TypeSerializer<W> getWindowSerializer(ExecutionConfig executionConfig);
    public abstract boolean isEventTime();
    public abstract static class WindowAssignerContext {
        public abstract long getCurrentProcessingTime();
    }
}
```

Window API: `MergingWindowAssigner`.

```
package org.apache.flink.streaming.api.windowing.assigners;

public abstract class MergingWindowAssigner<T, W extends Window>
  extends WindowAssigner<T, W> {
     public abstract void mergeWindows(Collection<W> windows,
                                       MergeCallback<W> callback);
    public interface MergeCallback<W> {
        void merge(Collection<W> toBeMerged, W mergeResult);
    }
}
```

Window API: Trigger.

```
package org.apache.flink.streaming.api.windowing.triggers;

public abstract class Trigger<T, W extends Window> implements Serializable {
    ...
     public abstract TriggerResult onElement(T element,
                                             long timestamp,
                                             W window,
                                             TriggerContext ctx) throws Exception;

     public boolean canMerge() { return false; }
     public void onMerge(W window,
                         OnMergeContext ctx) throws Exception { throws by default }

    ...
}
```

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Window API: Trigger.

```
package org.apache.flink.streaming.api.windowing.triggers;

public abstract class Trigger<T, W extends Window> implements Serializable {
    ...
     public abstract TriggerResult onProcessingTime(long time,
                                                    W window,
                                                    TriggerContext ctx) throws Exception;

     public abstract TriggerResult onEventTime(long time,
                                               W window,
                                               TriggerContext ctx) throws Exception;
    ...
}
```

Window API: Trigger.

```
package org.apache.flink.streaming.api.windowing.triggers;

public abstract class Trigger<T, W extends Window> implements Serializable {
    ...
    public abstract void clear(W window, TriggerContext ctx) throws Exception;
    public interface TriggerContext { ... }
    public interface OnMergeContext extends TriggerContext { ... }
    ...
}
```

Window API: Trigger.

```
package org.apache.flink.streaming.api.windowing.triggers;

public abstract class Trigger<T, W extends Window> implements Serializable {
    ...
    public interface TriggerContext {
        long getCurrentProcessingTime();
        MetricGroup getMetricGroup();
        long getCurrentWatermark();
        void registerProcessingTimeTimer(long time);
        void registerEventTimeTimer(long time);
        void deleteProcessingTimeTimer(long time);
        void deleteEventTimeTimer(long time);
        <S extends State> S getPartitionedState(StateDescriptor<S, ?> stateDescriptor);
    }

    public interface OnMergeContext extends TriggerContext {
        <S extends MergingState<?, ?>> void mergePartitionedState(StateDescriptor<S, ?> stateDescriptor);
    }
}
```

Window API: Evictor.

```
package org.apache.flink.streaming.api.windowing.evictors;

public interface Evictor<T, W extends Window> extends Serializable {
    void evictBefore(Iterable<TimestampedValue<T>> elements,
                     int size,
                     W window,
                     EvictorContext evictorContext);
    void evictAfter(Iterable<TimestampedValue<T>> elements,
                    int size,
                    W window,
                    EvictorContext evictorContext);
    ...
}
```

Window API: Evictor.

```
package org.apache.flink.streaming.api.windowing.evictors;

public interface Evictor<T, W extends Window> extends Serializable {
    ...
    interface EvictorContext {
        long getCurrentProcessingTime();
        MetricGroup getMetricGroup();
        long getCurrentWatermark();
    }
}
```

The solution

in detail.

Custom Window: `WindowAssigner`.

```
public class CustomWindowAssigner<E extends CustomEvent> extends MergingWindowAssigner<E, CustomWindow<E>> {
    ...
    @Override
    public Collection<CustomWindow<E>> assignWindows(E element,
                                                       long timestamp,
                                                       WindowAssignerContext context) {
        return Collections.singletonList(new CustomWindow<>(element, timeoutDuration));
    }
    ...
}
```

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Custom Window: `Window`.

```
public class CustomWindow<E extends CustomEvent> extends Window {
    ...
    @Override
    public long maxTimestamp() {
            return maxTimestamp;
    }
    ...
}
```

Custom Window: `Window`.

```
public class CustomWindow<E extends CustomEvent> extends Window {
    ...
     @Override
     public boolean equals(Object o) {
         // important: equals implementation must compare using “value” semantics
     }

     @Override
     public int hashCode() {
         // important: same for hashCode implementation
     }
    ...
}
```

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Custom Window: `Window.`

```
public class CustomWindow<E extends CustomEvent> extends Window {
    ...
    public static class Serializer<T extends CustomEvent>
                                    extends TypeSerializer<CustomWindow<T>> {
        ...
    }
    ...
}
```

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Custom Window: `Window`.

```
public class CustomWindow<E extends CustomEvent> extends Window {
    ...
    public static class Serializer<T extends CustomEvent>
                                 extends TypeSerializer<CustomWindow<T>> {
        @Override
        public boolean isImmutableType() { return true; }
        ...
    }
    ...
}
```

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Custom Window: `Window`.

```
public class CustomWindow<E extends CustomEvent> extends Window {
    ...
    public static class Serializer<T extends CustomEvent> extends TypeSerializer<CustomWindow<T>> {
        ...
         @Override
         public TypeSerializer<CustomWindow<T>> duplicate() { return this; }
         @Override
         public CustomWindow<T> createInstance() { return null; }
         @Override
         public CustomWindow<T> copy(CustomWindow<T> from) { return from; }
         @Override
         public CustomWindow<T> copy(CustomWindow<T> from, CustomWindow<T> reuse) { return from; }
         @Override
         public int getLength() { return -1; }
    }
    ...
}
```

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Custom Window: `Window`.

```
public class CustomWindow<E extends CustomEvent> extends Window {
    ...
    public static class Serializer<T extends CustomEvent> extends TypeSerializer<CustomWindow<T>> {
        ...
        public void serialize(CustomWindow<T> record, DataOutputView target)
          throws IOException {
            serializeStartEvent(record, target);
            target.writeLong(record.getDuration().toMillis());
            target.writeBoolean(record.evaluate());
            final boolean hasEndEventData = record.getEndEventData() != null;
            target.writeBoolean(hasEndEventData);
            if (hasEndEventData) serializeEndEvent(record, target);
        }
    }
    ...
}
```

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Custom Window: `Window.`

```
public class CustomWindow<E extends CustomEvent> extends Window {
    ...
    public static class Serializer<T extends CustomEvent> extends TypeSerializer<CustomWindow<T>> {
        ...
        @Override
        public CustomWindow<T> deserialize(DataInputView source) throws IOException {
            final T startEvent = deserializeStartEvent(source);
            final Duration duration = Duration.ofMillis(source.readLong());
            final boolean evaluate = source.readBoolean();
            final boolean hasEndEventData = source.readBoolean();
            final T endEvent = hasEndEventData ? deserializeEndEvent(source) : null;
            return new CustomWindow<>(startEvent, duration, endEvent, evaluate);
        }
    }
    ...
}
```

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Custom Window: `Window`.

```
public class CustomWindow<E extends CustomEvent> extends Window {
    ...
    public static class Serializer<T extends CustomEvent> extends TypeSerializer<CustomWindow<T>> {
        ...
        @Override
        public CustomWindow<T> deserialize(CustomWindow<T> reuse,
                                           DataInputView source) throws IOException {
            return reuse != null ? reuse : deserialize(source);
        }
    }
    ...
}
```

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Custom Window: `Window`.

```
public class CustomWindow<E extends CustomEvent> extends Window {
    ...
    public static class Serializer<T extends CustomEvent> extends TypeSerializer<CustomWindow<T>> {
        ...
        @Override
        public void copy(DataInputView source, DataOutputView target) throws IOException {
            // slightly less efficient, but more maintainable
            CustomWindow<T> deserializedWindow = deserialize(source);
            serialize(deserializedWindow, target);
        }
    }
    ...
}
```

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Custom Window: `Window`.

```
public class CustomWindow<E extends CustomEvent> extends Window {
    ...
    public static class Serializer<T extends CustomEvent> extends TypeSerializer<CustomWindow<T>> {
        ...
            @Override
            public boolean equals(Object obj) { return obj instanceof Serializer; }
            @Override
            public boolean canEqual(Object obj) { return obj instanceof Serializer; }
            @Override
            public int hashCode() { return 0; }
    }
    ...
}
```

Custom Window: `Window`.

```
public class CustomWindow<E extends CustomEvent> extends Window {
    ...
    public static class Serializer<T extends CustomEvent> extends TypeSerializer<CustomWindow<T>> {
        ...
        @Override
        public TypeSerializerConfigSnapshot snapshotConfiguration() { ... }
        @Override
        public CompatibilityResult<CustomWindow<T>> ensureCompatibility(
                TypeSerializerConfigSnapshot configSnapshot) {
            return CompatibilityResult.requiresMigration();
        }
        private static class CustomWindowSerializerConfigSnapshot extends TypeSerializerConfigSnapshot {
            ...
        }
    }
    ...
}
```

Custom Window: `Window`.

```
public class CustomWindow<E extends CustomEvent> extends Window {
    …
    public CustomWindow(@Nonnull D primaryEventData,
                        @Nonnull Duration timeoutDuration,
                        D endEventData,
                        boolean evaluate) {
        ...
          this.endTimestamp = endEventData != null ?
                                     endEventData.getTimestamp() : maxTimestamp;
        ...
    }
    ...
     public boolean evaluate() { return evaluate; }
     public Instant startTimestamp() { return primaryEventData.getTimestamp(); }
     public Instant endTimestamp() { return endTimestamp; }
    }
    ...
}
```

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Custom Window: `WindowAssigner`.

```
public class CustomWindowAssigner<E extends CustomEvent> extends MergingWindowAssigner<E, CustomWindow<E>> {
    ...
    @Override
    public void mergeWindows(Collection<CustomWindow<E>> mergeCandidates,
                             MergeCallback<CustomWindow<E>> mergeCallback) {

        final CustomWindow<E> sessionWindow = calculateSessionWindow(mergeCandidates);

        final Collection<CustomWindow<E>> inWindow = filterWithinWindow(mergeCandidates);

        // MergeCallback#merge implementation expects 2 or more.
        if (inWindow.size() > 1) {
            mergeCallback.merge(inWindow, sessionWindow);
        }
    }
    ...
}
```

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Custom Window: `WindowAssigner`.

```
public class CustomWindowAssigner<E extends CustomEvent> extends MergingWindowAssigner<E, CustomWindow<E>> {
    ...
    private CustomWindow<E> calculateSessionWindow(Collection<CustomWindow<E>> mergeCandidates) {

        CustomWindow<E> startEventWindow = findStartEventWindow(mergeCandidates);

        if (startEventWindow != null) {  // valid window
            ...
        } else {  // exploratory window
            ...
        }
    }
    ...
}
```

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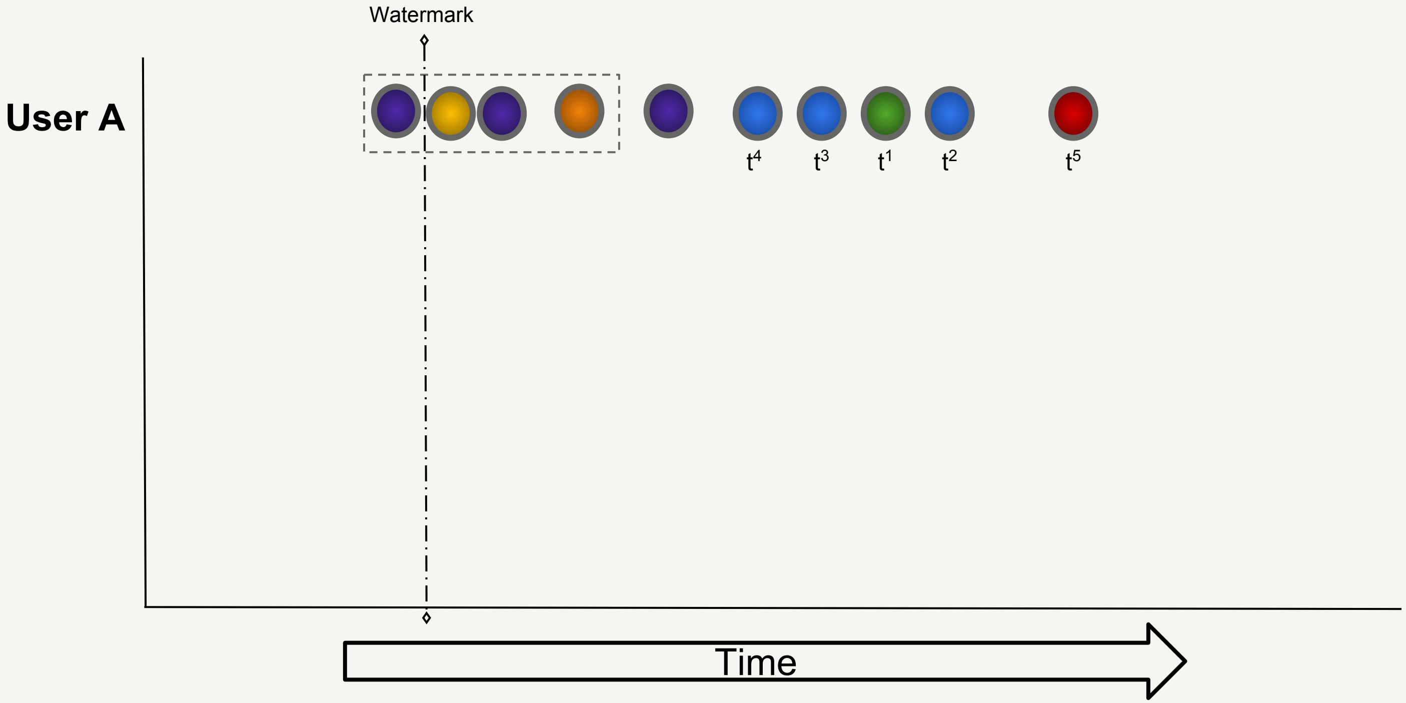
Custom Window: `WindowAssigner`.

```
if (startEventWindow != null) {  // valid window
    CustomWindow<E> endEvent = findEndEventWindow(mergeCandidates); // can return null

    return new CustomWindow<>(startEventWindow.getEvent, timeoutDuration, endEvent,
                              true); // fire (send this one to the WindowFunction)
} else {  // exploratory window
    ...
}
```

Custom Window: `WindowAssigner`.

```
if (startEventWindow != null) {  // valid window
    ...
} else {  // exploratory window
    CustomWindow<E> window = findClosestToMidpointByStartTime(mergeCandidates);
    return new CustomWindow(window.getEvent, explorat oryDuration,
                                        false) // just purge without firing
}
```



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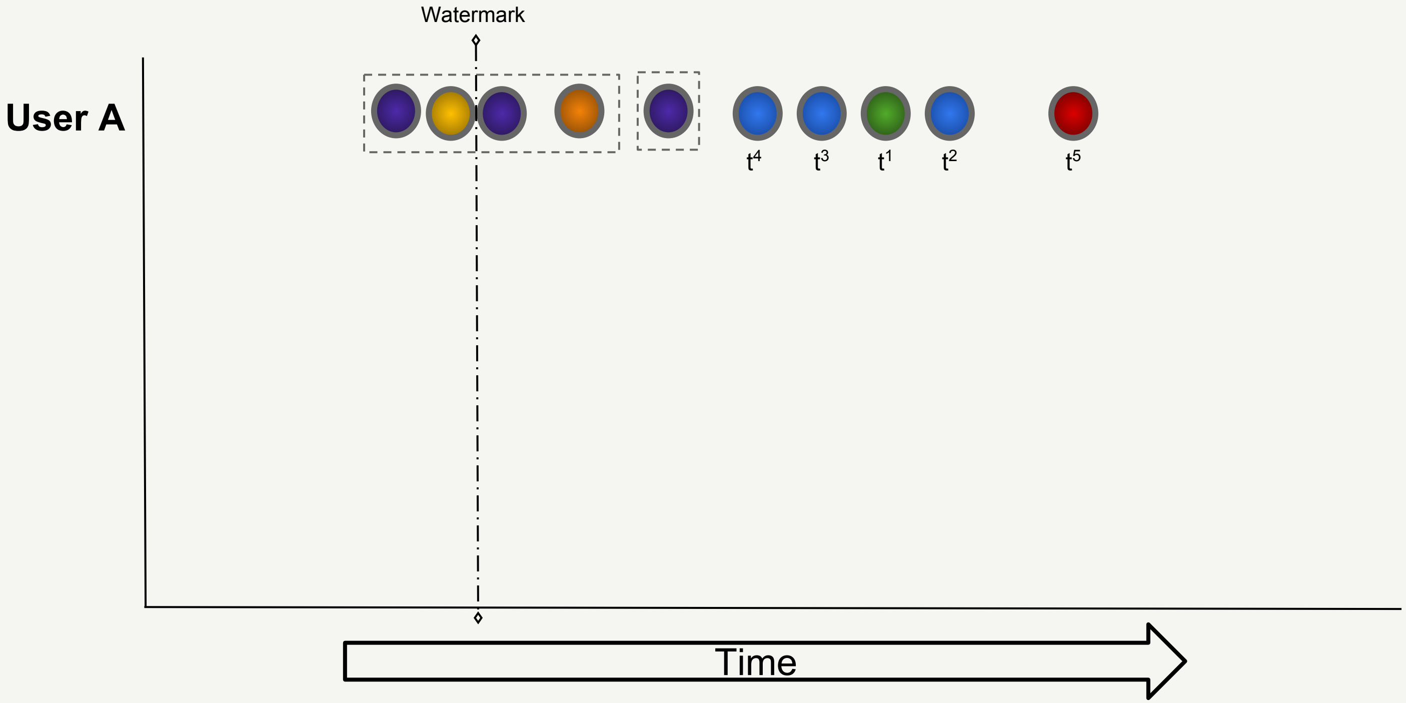
Watermark
User A
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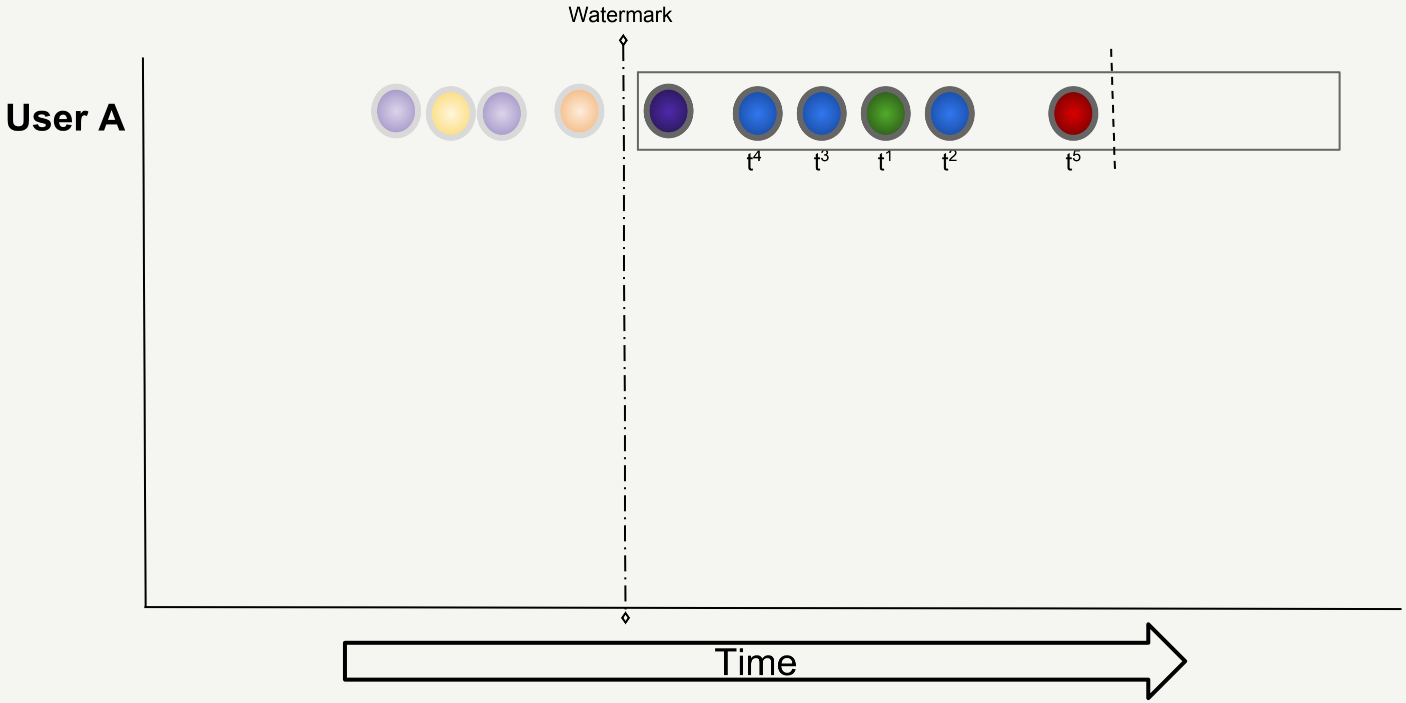
t^1
t^2
t^5
Time



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Custom Window: Trigger.

```
public class CustomWindowTrigger<E extends CustomEvent> extends Trigger<E, CustomWindow<E>> {
    ...
     @Override
     public boolean canMerge() { return true; }

     @Override
     public void onMerge(CustomWindow<E> window, OnMergeContext onMergeContext)
       throws Exception {
         onMergeContext.registerEventTimeTimer(window.endTimestamp().toEpochMilli());
     }
    ...
}
```

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Custom Window: Trigger.

```
public class CustomWindowTrigger<E extends CustomEvent> extends Trigger<E, CustomWindow<E>> {
    ...
    @Override
    public TriggerResult onElement(E element, long timestamp, CustomWindow<E> window,
                                   TriggerContext triggerContext) throws Exception {
        final TriggerResult triggerResult;
        final ValueState<Boolean> windowClosedState =
                triggerContext.getPartitionedState(windowClosedDescriptor);
        final long endTimestamp = window.endTimestamp().toEpochMilli();
        if (triggerContext.getCurrentWatermark() >= endTimestamp) {
            triggerResult = windowClosedState.value() ? TriggerResult.CONTINUE
                    : triggerWindow(triggerContext, windowClosedState, window);
        } else {
            ...
        }
        return triggerResult;
    }
    ...
}
```

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Custom Window: Trigger.

```
public class CustomWindowTrigger<E extends CustomEvent> extends Trigger<E, CustomWindow<E>> {
    ...
    private TriggerResult triggerWindow(TriggerContext triggerContext,
                                        ValueState<Boolean> windowClosedState,
                                        CustomWindow<E> window) throws IOException {
        windowClosedState.update(Boolean.TRUE);
        removeEarlyFiringTimer(triggerContext);
        return window.evaluate() ? TriggerResult.FIRE_AND_PURGE : TriggerResult.PURGE;
    }
    private void removeEarlyFiringTimer(TriggerContext triggerContext) throws IOException {
        final ValueState<Long> earlyFiringState =
                triggerContext.getPartitionedState(earlyFiringDescriptor);
        if (earlyFiringState.value() > 0) {
            triggerContext.deleteProcessingTimeTimer(earlyFiringState.value());
            // set to -1L to differentiate from the default value
            earlyFiringState.update(-1L);
        }
    }
    ...
}
```

Custom Window: `Trigger`.

```
public class CustomWindowTrigger<E extends CustomEvent> extends Trigger<E, CustomWindow<E>> {
    ...
    @Override
    public TriggerResult onElement(E element, long timestamp, CustomWindow<E> window,
                                   TriggerContext triggerContext) throws Exception {
        final TriggerResult triggerResult;
        final long endTimestamp = window.endTimestamp().toEpochMilli();
        final ValueState<Boolean> windowClosedState =
                triggerContext.getPartitionedState(windowClosedDescriptor);
        if ...
        } else {
            windowClosedState.update(Boolean.FALSE);
            triggerResult = TriggerResult.CONTINUE;
            triggerContext.registerEventTimeTimer(endTimestamp);
            registerEarlyFiringTimerIfNecessary(window, triggerContext);
        }
        return triggerResult;
    }
    ...
}
```

Custom Window: Trigger.

```
public class CustomWindowTrigger<E extends CustomEvent> extends Trigger<E, CustomWindow<E>> {
    ...
    private void registerEarlyFiringTimerIfNecessary(CustomWindow<E> window,
                                                     TriggerContext triggerContext)
      throws IOException {
        if (!window.evaluate() || earlyFiringInterval.toMillis() < 1) return;

        final ValueState<Long> earlyFiringState = triggerContext.getPartitionedState(earlyFiringDescriptor);

        if (earlyFiringState.value() == Long.MIN_VALUE) {
            final Long newEarlyFiringTimestamp = System.currentTimeMillis() + earlyFiringInterval.toMillis();
            if (newEarlyFiringTimestamp < window.endTimestamp().toEpochMilli()) {
                triggerContext.registerProcessingTimeTimer(newEarlyFiringTimestamp);
                earlyFiringState.update(newEarlyFiringTimestamp);
            }
        }
    }
    ...
}
```

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Custom Window: Trigger.

```
private void registerEarlyFiringTimerIfNecessary(CustomWindow<E> window,
                                                 TriggerContext triggerContext)
  throws IOException {
    if (!window.evaluate() || earlyFiringInterval.toMillis() < 1) return;

  final ValueState<Long> earlyFiringState =
          triggerContext.getPartitionedState(earlyFiringDescriptor);

  if (earlyFiringState.value() == Long.MIN_VALUE) {
  final Long newEarlyFiringTimestamp =
          System.currentTimeMillis() + earlyFiringInterval.toMillis();

    if (newEarlyFiringTimestamp < window.endTimestamp().toEpochMilli()) {
        triggerContext.registerProcessingTimeTimer(newEarlyFiringTimestamp);
        earlyFiringState.update(newEarlyFiringTimestamp);
    }
}
```

Custom Window: Trigger.

```
public class CustomWindowTrigger<E extends CustomEvent> extends Trigger<E, CustomWindow<E>> {
    ...
    @Override
    public TriggerResult onEventTime(long time,
                                     CustomWindow<E> window,
                                     TriggerContext triggerContext) throws Exception {
        if (time != window.endTimestamp().toEpochMilli()) {
            return TriggerResult.CONTINUE;
        }

        final ValueState<Boolean> windowClosedState =
                triggerContext.getPartitionedState(windowClosedDescriptor);
        if (windowClosedState.value()) {
            return TriggerResult.CONTINUE;
        }

        return triggerWindow(triggerContext, windowClosedState, window);
    }
    ...
}
```

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Custom Window: Trigger.

```
public class CustomWindowTrigger<E extends CustomEvent> extends Trigger<E, CustomWindow<E>> {
    ...
    @Override
    public TriggerResult onEventTime(long time,
                                     CustomWindow<E> window,
                                     TriggerContext triggerContext) throws Exception {

        if (time != window.endTimestamp().toEpochMilli()) {
            return TriggerResult.CONTINUE;
        }

        final ValueState<Boolean> windowClosedState =
                triggerContext.getPartitionedState(windowClosedDescriptor);
        if (windowClosedState.value()) {
            return TriggerResult.CONTINUE;
        }

        return triggerWindow(triggerContext, windowClosedState, window);
    }
    ...
}
```

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Custom Window: Trigger.

```
public class CustomWindowTrigger<E extends CustomEvent> extends Trigger<E, CustomWindow<E>> {
    ...
     @Override
     public TriggerResult onProcessingTime(long time,
                                          CustomWindow<E> window,
                                          TriggerContext triggerContext) throws Exception {
         TriggerResult triggerResult = TriggerResult.CONTINUE;
         if (window.evaluate()) {
             ...
         }
         return triggerResult;
      }
    ...
}
```

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Custom Window: Trigger.

```
if (window.evaluate()) { // Update early firing
    final ValueState<Long> earlyFiringState =
            triggerContext.getPartitionedState(earlyFiringDescriptor);

    final Long newEarlyFiringTimestamp =
            earlyFiringState.value() + earlyFiringInterval.toMillis();

    if (newEarlyFiringTimestamp < window.endTimestamp().toEpochMilli()) {
        triggerContext.registerProcessingTimeTimer(newEarlyFiringTimestamp);
        earlyFiringState.update(newEarlyFiringTimestamp);
    }

    triggerResult = TriggerResult.FIRE;
}
return triggerResult;
```

Pitfall:

Window `equals` / `hashCode`.

Pitfall:

Metrics and Logs.

Pitfall:

Event Design.

Pitfall:

Large State.

Alternative:

```
ProcessFunction
```

Alternative:

`CEP Library`

- Motivating Use Cases.
- Window Requirements.
- The Solution (Conceptual).
- Event Processing Flow.
- Apache Flink Window API Walk-Through.
- The Solution (Detail).
- Pitfalls to Watch Out For.
- Alternative Implementations.
- Questions.

Thank You!

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