Tutorial: Synchro-waveform Data Analytics and Applications

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Motivation

\[ v(t) = |V|\cos(\omega t + \angle V) \]

Sensor: Phasor Measurement Unit (PMU)

FFT \mapsto Fundamental Component

Phasor Representation
Motivation

\[ v(t) = |V| \cos(\omega t + \angle V) \]

- **FFT** \(\mapsto\) **Fundamental Component**
- **Phasor Representation**
- **GPS Satellites**
- **Sensor: Phasor Measurement Unit (PMU)**
- **FFT \(\mapsto\) Fundamental Component**
Motivation

\[ v(t) = |V| \cos(\omega t + \angle V) \]

Time Reference

Sensor: Phasor Measurement Unit (PMU)

FFT \mapsto \text{Fundamental Component}

Phasor Representation

GPS Satellites
Motivation

\[ v(t) = |V| \cos(\omega t + \angle V) \]

**Phasor Representation**

**Synchro-waveform Data Analytics and Applications**

Sensor: Phasor Measurement Unit (PMU)

FFT \( \leftrightarrow \) Fundamental Component

GPS Satellites
Agenda

• Fundamentals
  • Waveform: Real-World Examples
  • Waveform Measurement Unit
  • Synchro-Waveforms

• Data-Analytics Methodologies
  • Detection
  • Location Identification
  • Characterization and Classification

• Applications

• Further Reading
Waveform: Real-World Examples

- Example 1 (Voltage Sag):

  - Looking at voltage waveform is *not necessary* in this example.

  ![Phasor (Magnitude)](image1)
  ![Waveform](image2)
Example 2 (Resonance):

We cannot see the high-frequency resonance in the phasors.
Waveform: Real-World Examples

- Example 3 (Fault):

![Phasor Waveform](image)

- Waveforms show much more details in this example.
Waveform Measurement Unit

• The device to measure voltage and current waveform:
  
  • **WMU**: Waveform Measurement Unit\(^1\)

    (Compare it with **PMU**: Phasor Measurement Unit)

• WMU is a generic term. The actual sensor might be called:
  
  • Power Quality Meter
  
  • Digital Fault Recorder (DFR)  (They all measure waveform)
  
  • Point-on-Wave (POW) Sensor

Waveform Measurement Unit

- WMUs can measure both voltage and current waveforms:

- Measured by the same WMUs (over 12 terminals):
Synchro-Waveforms

• Two Concepts:

**Synchro-Phasors** = Phasors + Time Synchronization

**Synchro-Waveforms** = Waveforms + Time Synchronization

• Analysis of Synchro-Waveforms is the focus in this Tutorial.
• Synchro-Waveforms in Example 3:
Synchro-Waveforms

- Synchro-Waveforms in Example 3:
Another Example - Synchro-Waveforms:

(Event is Likely Far from both WMU 1 and WMU 2)
• Synchro-Waveforms in the example with Resonance:

**WMU 1**

**Time Synchronized**

**WMU 3**

Another Location

(Also, Different Voltage Level)

(System-Wide Sub-Cycle Resonance, Seen at Multiple Substations)
• Synchro-Waveforms in the example with Resonance:

![Graphs showing Synchro-Waveforms](image)

WMU 1 and WMU 3 are Time Synchronized.

• WMUs observe the same physical phenomena at different locations.

  - Synchro-Waveform Situational Awareness
  - Covering Various Event Signatures (Sub-Cycle, Few-Cycle, etc.)
Synchro-Waveforms

- Field Measurements:

  - Single-Phase (120 V)
  - Three-Phase (480 V)
  - Three-Phase (12.47 kV)

  - Single-Phase (120 V)

  - Three-Phase (12.47 kV)

  - Three-Phase (480 V)
• **Example**: Phasor Measurements During an Event:

![Magnitude vs Time](image1)

![Angle vs Time](image2)
WMUs versus PMUs versus H-PMUs

- **Example:** Phasor Measurements During an Event:

![Graphs showing magnitude and angle with different harmonics for PMU and H-PMU.]
• **Note**: Adding *harmonic phasor data* is helpful:

• **Example**: Improvement in Event Clustering\(^2\) \rightarrow 13\% Improvement

---

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  • **Example**: Improvement in Event Clustering\(^2\) → 13% Improvement

• **Question**: Why limit ourselves to “phasor” representation?

---

WMUs versus PMUs versus H-PMUs

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WMUs versus PMUs versus H-PMUs

• **Note**: Adding *harmonic phasor data* is helpful:

  • **Example**: Improvement in Event Clustering \(^2\) → 13% Improvement

• **Question**: Why limit ourselves to “phasor” representation?

---

• **Situational awareness** with synchro-waveform data:
  
  • Data Size Per WMU: **3,981,312,000 Readings Per Day**
  
  • One Pair of WMUs: 8 Billion Data Points Per Day

• Event-Driven Data Analytics:
  
  – Event Detection
  
  – Event Location Identification
  
  – Event Characterization / Classification
• **Situational awareness** with synchro-waveform data:
  
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  • Event-Driven Data Analytics:
    
    – **Event Detection**
    
    – Event Location Identification
    
    – Event Characterization / Classification
Event Detection

- Let’s distinguish two cases:

  - Harmonic Distortions
  - Event
Let’s distinguish two cases:

Harmonic Distortions

(Steady-State Analysis\(^3\) \(\mapsto\) H-PMUs)

Event

Let’s distinguish two cases:

Harmonic Distortions

(Steady-State Analysis$^3 \rightarrow$ H-PMUs)

Event

Our Focus in This Section

---

• Event-triggered waveform capture:
• In practice, it is common to simply *compare two consecutive cycles*:
Event Detection

- In practice, it is common to simply compare two consecutive cycles:

What Metric?
Different ways to compare two cycles of waveforms:

- Comparing THD
- Comparing RMS
- Point-to-Point Comparison
- Comparing Sub-Cycle RMS
- Differential Waveform
- Neutral Current Waveform
- Other Factors and Methods
Event Detection

- Different ways to compare two cycles of waveforms\(^1\):
  - Comparing THD
  - Comparing RMS
  - Point-to-Point Comparison
  - Comparing Sub-Cycle RMS
  - Differential Waveform
  - Neutral Current Waveform
  - Other Factors and Methods
Comparing THD

• Compare two consecutive waveform cycles based on their THD values.

$|\Delta \text{THD}| \geq \alpha_{\text{THD}}$

THD = Total Harmonic Distortion

THD = 16%
Event Detection

Differential Waveform

• It works based on obtaining the following differential waveform:

\[ \Delta x(t) = x(t) - x(t - NT). \]

where

- \( x(t) \) is the measured current waveform or voltage waveform;
- \( T \) is the waveform interval; and
- \( N \) is a small integer number, e.g., 1, 2, 3, 4, or 5.

• We can detect an event based on the characteristics of \( \Delta x(t) \).
**Differential Waveform**

- Consider the current waveform measurements below:

\[
x(t)
\]

\[
x(t - T)
\]
Event Detection

**Differential Waveform**

- The differential waveform is obtained as:

  ![Differential Waveform Graph](image)

- We can see that the event has created two distinct blips in the differential waveform, which are denoted by 1 and 2.

- Note that *both* of them are associated with the *same* event.
Differential Waveform

- The differential waveform is obtained as:

We can see that the event has created two distinct blips in the differential waveform, which are denoted by ① and ②.

- Note that both of them are associated with the same event.
Neutral Current Waveform

- Consider the following three-phase current waveform measurements:

![Graph showing a phase of the event and the other two phases.](image-url)
Neutral Current Waveform

• The neutral current is obtained as:

\[ i_N(t) = i_A(t) + i_B(t) + i_C(t). \]

• **Note**: No second blip, unlike in the differential waveforms.
Neutral Current Waveform

• The neutral current is obtained as:

\[ i_N(t) = i_A(t) + i_B(t) + i_C(t). \]

• **Note**: No second blip, unlike in the differential waveforms.
Event Detection – Multiple Waveforms

• We may also try to *simultaneously* check multiple waveforms.

• For example, suppose two WMUs collect the following waveforms:
  
  • Voltage at WMU 1: \( v_1(t) \)
  
  • Current at WMU 1: \( i_1(t) \)
  
  • Voltage at WMU 2: \( v_2(t) \)
  
  • Current at WMU 2: \( i_2(t) \)
Event Detection – Multiple Waveforms

• We may also try to *simultaneously* check multiple waveforms.

• For example, suppose two WMUs collect the following waveforms:

  • Voltage at WMU 1: $v_1(t) \rightarrow \text{Detect}$
  • Current at WMU 1: $i_1(t) \rightarrow \text{Detect}$
  • Voltage at WMU 2: $v_2(t) \rightarrow \text{Detect}$
  • Current at WMU 2: $i_2(t) \rightarrow \text{Detect}$

We can look for event in *each* waveform.
Event Detection – Multiple Waveforms

- We may also try to *simultaneously* check multiple waveforms.

- For example, suppose two WMUs collect the following waveforms:
  - Voltage at WMU 1: $v_1(t)$
  - Current at WMU 1: $i_1(t)$
  - Voltage at WMU 2: $v_2(t)$
  - Current at WMU 2: $i_2(t)$

We can look for event in *all* waveforms.
Event Detection – Multiple Waveforms

- **Graphical Metrics**:  

  **Location 1 / WMU 1**  
  $v_1(t), i_1(t)$

  **Location 2 / WMU 2**  
  $v_2(t), i_2(t)$

  $v(t) = v_1(t) - v_2(t)$

  $i(t) = i_1(t) - i_2(t)$

  **Lissajous Graph**

  **Area**  
  $A(t)$

  $\text{Area} = \left| \int_{\tau=t-T}^{\tau=t} v(t) \, di(t) \right|$

  **Similarity Index**  
  $S(t) = 1 - \left| \frac{A(t) - A(t-T)}{\max\{A(t), A(t-T)\}} \right|$

---

• Situational awareness with synchro-waveform data:
  
  • Data Size Per WMU: 3,981,312,000 Readings Per Day
  
  • One Pair of WMUs: 8 Billion Data Points Per Day
  
  • Event-Driven Data Analytics:
    – Event Detection
    – Event Location Identification
    – Event Characterization / Classification
Synchro-Waveform Data Analysis

- **Situational awareness** with synchro-waveform data:
  - Data Size Per WMU: **3,981,312,000 Readings Per Day**
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- Event-Driven Data Analytics:
  - Event Detection
  - **Event Location Identification**
  - Event Characterization / Classification
Event Location Identification

- Finding the Cause of Transient Events:
Event Location Identification

- Finding the Cause of Transient Events:

![Diagram showing event location identification on a transmission line with substations labeled WMU 1 and WMU 2, and a voltage graph illustrating an event at a specific time (msec)].
Event Location Identification

- Finding the Cause of Transient Events:

![Diagram showing substation and WMUs with an event causing a voltage change](image)

- Extract $v_{\text{event}}(t)$
Event Location Identification

- Finding the Cause of Transient Events:

\[ v(t) \]

\[ v_{\text{event}}(t) \]

Modal Analysis

Number of Modes

\[ \sum_{p=1}^{P} A_{p,m} e^{\sigma_p t} \cos(2\pi f_p t + \theta_p) \]

Damping Sinusoidal Modes

\[ (f_p, \sigma_p, A_{p,m}, \theta_p) \]

Extract \( v_{\text{event}}(t) \)
Event Location Identification

- Multi-Signal Modal Analysis:

\begin{align*}
\nu_1(t), \ i_1(t), \ \nu_2(t), \ i_2(t)
\end{align*}

\begin{table}
\begin{tabular}{|c|c|c|c|c|}
\hline
WMU & Signal & Frequency (Hz) & Damping Rate (Hz) & Magnitude (p.u.) & Phase Angle (deg.) \\
\hline
1 & Voltage & 60.00 / 747.72 & 0.00 / -624.30 & 0.98 / 0.20 & 0.00 / 0.00 \\
& Current & & & 0.04 / 0.06 & -25.19 / 82.43 \\
& Voltage & & & 0.96 / 0.92 & -0.49 / -1.07 \\
& Current & & & 0.004 / 0.004 & -25.96 / -3.23 \\
\hline
\end{tabular}
\end{table}

* The two most dominant modes are separated with a slash.
Accordingly, we can solve the circuit in “event mode”.

- This means solving the circuit based on $\omega, \sigma$ (instead of over $\omega_0$)
• Circuit model under the event mode$^5$:

\[
\begin{align*}
\text{WMU 1} & \quad \omega, \sigma, A_1, \theta_1 \\
\text{WMU 2} & \quad \omega, \sigma, A_8, \theta_8
\end{align*}
\]

Event Location Identification

- Circuit model under the event mode\textsuperscript{5}:

\[
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\text{WMU 1} & : \omega, \sigma, A_1, \theta_1 \\
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\textbf{Event Bus}

Event Location Identification

- Circuit model under the event mode⁵:

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\end{align*}
\]

Step 1: Forward Sweep (Event Mode)

\[V_1^f, V_2^f, \ldots, V_7^f, V_8^f\]

(Phasors in Event Mode; not in Fundamental Mode)

---

Event Location Identification

- Circuit model under the event mode\(^5\):

\[ \omega, \sigma, A_1, \theta_1 \]

\[ \omega, \sigma, A_8, \theta_8 \]

Step 2: Backward Sweep (Event Mode)

\[ V_1^b, V_2^b, ..., V_7^b, V_8^b \]

(Phasors in Event Mode; \textit{not} in Fundamental Mode)

Event Location Identification

- Circuit model under the event mode\(^5\):

\[ k^* = \text{argmin}_i \Psi_i \quad \text{where} \quad \Psi_i = |V_i^f - V_i^b|, \quad i = 1, \ldots, 8. \]

Event Location Identification

- We may have more than two WMUs available:

- Several Options:
  1) WMU 1 and WMU 2
  2) WMU 1 and WMU 3
  3) WMU 1 and WMU 4
  4) WMU 1 and WMU 5
Event Location Identification

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We may have more than two WMUs available:

1) WMU 1 and WMU 2
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\[ k^* = \arg\min_i \sum_{s=2}^{5} \psi_{i,s} \]
Event Location Identification

- IEEE 33-Bus Test System (PSCAD Simulations)\(^5\):

Event Location Identification

- IEEE 33-Bus Test System (PSCAD Simulations)\(^5\):

\[ \text{WMUs 1 and 2} \]

\[ \text{Event Bus, } k = 9 \]

---

IEEE 33-Bus Test System (PSCAD Simulations)\textsuperscript{5}:

\textbf{WMUs 1 and 3}

Event Location Identification

- IEEE 33-Bus Test System (PSCAD Simulations)\(^5\):

\[ \text{Event Bus, } k = 9 \]

\[ \text{All Five WMUs} \]

• Impact of *Harmonic Distortion* and *Measurement Noise*:

<table>
<thead>
<tr>
<th>THD (%)</th>
<th>SNR (dB)</th>
<th>Correct Bus</th>
<th>Neighboring Bus</th>
<th>Other Bus</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>80</td>
<td>100.0 %</td>
<td>0.0 %</td>
<td>0.0 %</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>100.0 %</td>
<td>0.0 %</td>
<td>0.0 %</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>86.8 %</td>
<td>5.8 %</td>
<td>7.4 %</td>
</tr>
<tr>
<td>2</td>
<td>80</td>
<td>100.0 %</td>
<td>0.0 %</td>
<td>0.0 %</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>99.9 %</td>
<td>0.1 %</td>
<td>0.0 %</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>84.4 %</td>
<td>7.5 %</td>
<td>8.1 %</td>
</tr>
<tr>
<td>3</td>
<td>80</td>
<td>100.0 %</td>
<td>0.0 %</td>
<td>0.0 %</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>99.8 %</td>
<td>0.2 %</td>
<td>0.0 %</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>85.5 %</td>
<td>6.2 %</td>
<td>8.3 %</td>
</tr>
</tbody>
</table>

• Impact of *Error in Line Parameters*:

<table>
<thead>
<tr>
<th>Error (%)</th>
<th>Correct Bus</th>
<th>Neighboring Bus</th>
<th>Other Bus</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>100.0 %</td>
<td>0.0 %</td>
<td>0.0 %</td>
</tr>
<tr>
<td>50</td>
<td>98.9 %</td>
<td>1.1 %</td>
<td>0.0 %</td>
</tr>
<tr>
<td>75</td>
<td>93.0 %</td>
<td>7.0 %</td>
<td>0.0 %</td>
</tr>
<tr>
<td>100</td>
<td>85.8%</td>
<td>14.2 %</td>
<td>0.0 %</td>
</tr>
</tbody>
</table>
**Synchro-Waveform Data Analysis**

- **Situational awareness** with synchro-waveform data:
  - Data Size Per WMU: \(3,981,312,000\) Readings Per Day
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Event-Driven Data Analytics:

- Event Detection
- Event Location Identification
- Event Characterization / Classification
Event Characterization

• Example **Feature Extraction** in Waveform Measurements¹:

  • Angle, Magnitude, and Duration
  • Number of Affected Phases
  • Transient Oscillations
  • Transient Impulses
  • Fault-Specific Features
  • Changes in Steady-State Characteristics
  • Time, Season, and Location
  • Other Basic Features
  • Graphical Features
Event Characterization

• Example **Feature Extraction** in Waveform Measurements¹:

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  • **Graphical Features**
Event Characterization

**Angle, Magnitude, and Duration**

- These basic features can be obtained for most events.

- An example for these three features for the case of a current waveform measurement during a self-clearing fault is shown below.

![Original waveform](image1)

![Differential waveform](image2)

Original waveform  Differential waveform
Transient Oscillations

- Transient oscillations in waveform measurements are described by the **magnitude**, **duration**, and **dominant frequency** of the oscillations.

![Graph showing waveform with annotations](image)

- 1 Cycle = 16.7 msec

- 1.2 kHz
Transient Oscillations

- The frequency of oscillations in waveform measurements can be obtained by using *modal analysis*; including the use of Fourier Analysis.

- The *dominant frequency* is about 1.2 KHz.
Event Characterization

**Transient Impulses**

- An *impulsive transient* is a sudden change in the waveform of voltage, current, or both, that is typically unidirectional in polarity.

- A common cause of impulsive transients is *lightning strike*. 

![Graph showing voltage amplitude over time](image-url)
Event Characterization

**Graphical Features**

- The Lissajous graphs can serve as *images* with graphical characteristics.

\[
v(t) = v_1(t) - v_2(t)\\
i(t) = i_1(t) - i_2(t)
\]
Graphical Features

• The Lissajous graphs can serve as *images* with graphical characteristics.

\[
v(t) = v_1(t) - v_2(t) \\
\]

\[
i(t) = i_1(t) - i_2(t) \\
\]

**Lissajous Graph**

**Pre-Event Shape**

**Location 1 / WMU 1**

\[v_1(t), i_1(t)\]

**Location 2 / WMU 2**

\[v_2(t), i_2(t)\]
Graphical Features

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Event Classification

- Characterization/Classification\(^6\):

High Impedance Fault

Capacitor Bank Switching

Incipient Fault

Event Classification

• Characterization/Classification:

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Incipient Fault

Event Classification

- Characterization/Classification\(^6\):

  **High Impedance Fault**

  **Capacitor Bank Switching**

  **Incipient Fault**

---

Event Classification

- Characterization/Classification\(^6\):

  **High Impedance Fault**

  ![Graphs showing high impedance fault patterns](image)

  **Capacitor Bank Switching**

  ![Graphs showing capacitor bank switching patterns](image)

  **Incipient Fault**

  ![Graphs showing incipient fault patterns](image)

---

Event Classification

- Classification with Convolutional Neural Network (CNN)\textsuperscript{6}:

Confusion Matrix:

\begin{tabular}{c|ccc}
 & Class I & Class II & Class III \\
\hline
True Class & \textbf{100.0}\% & \textbf{0.0}\% & \textbf{0.0}\% \\
Class I & \textbf{8.3}\% & \textbf{91.7}\% & \textbf{0.0}\% \\
Class II & \textbf{0.0}\% & \textbf{0.0}\% & \textbf{100.0}\% \\
Class III & & & \\
\end{tabular}

Performance:

\begin{tabular}{c|ccccc}
Class & Precision & Sensitivity & Specificity & F\textsubscript{1} Score \\
\hline
I & \textbf{100.0}\% & 92.3\% & 100.0\% & 96.0\% \\
II & \textbf{100.0}\% & 100.0\% & 100.0\% & 100.0\% \\
III & 94.4\% & 100.0\% & 96.8\% & 97.1\% \\
\end{tabular}

Applications of Situational awareness with synchro-waveform data:

- Event Detection
- Event Location Identification
- Event Characterization / Classification
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- Event Detection
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Incipient (Early-Stage) Faults

- Overhead Line
- Underground Cable
- Capacitor Bank
- Transformer
- Inverters
- Power Electronics
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Unique Signatures
Applications of Situational awareness with synchro-waveform data:

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Incipient (Early-Stage) Faults

- Overhead Line
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Wildfire Monitoring

Applications of Situational awareness with synchro-waveform data:

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Incipient (*Early-Stage*) Faults

- Overhead Line
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Inverter Response

<table>
<thead>
<tr>
<th>Inverter 1</th>
<th>Inverter 2</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Inverter 1 Voltage" /></td>
<td><img src="image2" alt="Inverter 2 Voltage" /></td>
</tr>
<tr>
<td><img src="image3" alt="Inverter 1 Current" /></td>
<td><img src="image4" alt="Inverter 2 Current" /></td>
</tr>
</tbody>
</table>

No Ride Through
Applications of Situational awareness with synchro-waveform data:

- Event Detection
- Event Location Identification
- Event Characterization / Classification

Incipient (Early-Stage) Faults

- Overhead Line
- Underground Cable
- Capacitor Bank
- Transformer
- Inverters
- Power Electronics
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And More!
Further Reading

- Chapter 4: Waveform and Power Quality Measurements and Their Applications

Textbook on Smart Grid Sensors:
- Working Principles
- Sample Data Sets
- Data-Driven Methods
  - Synchro-phasors
  - Synchro-waveforms
  - Smart meters
  - Building sensors
  - Power and energy
  - Probing

- And the references cited on the slides.
Thank You!

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