GALS Methodology for Substrate Noise Reduction in Mixed-Signal Integrated Circuits

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## Agenda

1. **Introduction**
2. Switching current spectrum optimization requirements for substrate noise reduction
3. Harmonic balanced partitioning
4. GALS partitioning algorithm for substrate noise reduction
5. Methodology for GALS partitioning
6. Conclusions and future work
Introduction – Substrate noise

- Gate switching:

  Gate switching → Current surges in the supply and ground lines (switching current)

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Introduction – Substrate noise

- Gate switching:
  - Gate switching $\rightarrow$ Current surges in the supply and ground lines (switching current)
  - Switching current $\rightarrow$ Voltage oscillations on supply and ground lines (supply and ground bounce)
Introduction – Substrate noise

- Ground bounce → Voltage fluctuations in the substrate (substrate noise)

- Direct coupling through substrate contacts → dominant coupling mechanism
- This noise further propagates to the outputs of analog circuits, impacting the performance
A single gate doesn’t produce a lot of ground bounce...
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... but the system has a huge number of simultaneously switching gates
Introduction – Substrate noise

- A single gate doesn’t produce a lot of ground bounce...
- ...but the system has a huge number of simultaneously switching gates

- Noise generation is, to a large extent, a system level effect, and thus can be addressed at system level
Introduction – Existing system level approaches for substrate noise reduction

- Spreading the switching activity in synchronous circuits
  - Introducing the intentional clock skew
  - Phase modulation of the clock
  - Pseudo-random clocking
Introduction – Existing system level approaches for substrate noise reduction

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- Asynchronous design approach

- GALS design approach
  - “GALS design for spectral peak attenuation of switching current” [10]

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Introduction – GALS design approach for spectral peak attenuation of switching current

“GALS design for spectral peak attenuation of switching current” [10]

- Switching current spectrum for a synchronous system:
  - Discrete peaks
  - Continuous noise floor

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“GALS design for spectral peak attenuation of \textit{switching current}” [10]

- Switching current spectrum for a synchronous system:
  - Discrete peaks
  - Continuous noise floor

- Switching current spectrum for a GALS system with $M$ LSMs:
  - Each synchronous peak replaced by $M$ GALS peaks
Introduction – GALS design approach for spectral peak attenuation of switching current

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- Plesiochronous clocking scheme with power-balanced partitioning

- Spectral peak attenuation at the fundamental:

  $$SPA_{dB} = 20 \log \frac{A_{1,\text{sync}}}{\max \{ A_{1m,GALS} \}} = 20 \log M$$

Introduction – GALS design approach for spectral peak attenuation of switching current

- "GALS design for spectral peak attenuation of switching current" [10]
  - Switching current spectrum for a synchronous system:
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  - Plesiochronous clocking scheme with power-balanced partitioning
  - Spectral peak attenuation at the fundamental:
    \[
    SPA_{dB} = 20 \log \frac{A_{1,\text{sync}}}{\max \{ A_{1m,GALS} \}} = 20 \log M
    \]

- The goal of this work:
  - Provide a corresponding methodology for substrate noise suppression

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Switching current and substrate noise spectra

- Switching current spectrum ($F\{i_{sw}\}$):
  - Fundamental is the dominant component $\rightarrow$ targeted by power balancing [10]
Switching current and substrate noise spectra

- Switching current spectrum \(F\{i_{sw}\} \):
  - Fundamental is the dominant component \(\rightarrow\) targeted by power balancing [10]

- Substrate noise spectrum \(F\{v_{sub}\} \):

\[
F\{v_{sub}\} = H_{sub} F\{v_{gb}\} = H_{sub} H_p F\{i_{sw}\} = H F\{i_{sw}\}
\]

\(F\{v_{gb}\} \) – ground bounce spectrum

\(H_{sub} \) – substrate transfer function (from aggressor substrate contacts to the victim)

\(F\{i_{sw}\} \) – switching current spectrum

\(H_p \) – package & PDN transfer function (from switching current to ground bounce)

\(H \) – total package & PDN and substrate transfer function (from switching current to the victim)

- \(H \) usually pass-band \(\rightarrow\) dominant components at higher frequency
Spectrum optimization requirements for substrate noise reduction

- Spectrum optimization goal:
  - The components dominantly impacting the functionality of analog blocks
  - Depends on the type of the analog blocks
Spectrum optimization requirements for substrate noise reduction

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- Sensitivity of different analog modules on substrate noise:
  - VCO:
    - Low frequency harmonics can form intermodulation products with an oscillator frequency and form spures in output spectrum → low frequencies are critical
  - LNA:
    - Mostly the in-band noise corrupts the performance → high frequencies are critical
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- Usually more than one type of analog modules on the chip

- Requirements:
  - Noise suppression at higher frequencies
  - Possibility of frequency selective noise suppression covering multiple frequency bands
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Plesiochronous clocking scheme

- LSMs have different clock frequencies
- Those frequencies are mutually close, and close to the clock frequency of the synchronous system
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Why plesiochronous?
- Maintains the processing capability of each of the LSMs
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Why plesiochronous?
- Maintains the processing capability of each of the LSMs
- Predictability
  - Substrate transfer function $H$ has different values at different frequencies
  - For close frequencies, the difference is values of $H$ is negligible

$$F_n\{v_{subm}\} = H_{nm} F_n\{i_m\}, \quad F_n\{v_{sub}\} = H_n F_n\{i\}$$

*same power domain for all the partitions + plesiochronous design $\rightarrow$ $H_{n1} \approx H_{n2} \approx \cdots \approx H_{nm} \approx H_n$*
Plesiochronous clocking scheme

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  - Substrate transfer function $H$ has different values at different frequencies
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  switching current peak attenuation = substrate noise peak attenuation

\[
F_n\{v_{subm}\} = H_{nm} F_n\{i_m\} , \quad F_n\{v_{sub}\} = H_n F_n\{i\}
\]

same power domain for all the partitions + plesiochronous design \(\rightarrow\)
\(\rightarrow\) $H_{n1} \approx H_{n2} \approx \cdots \approx H_{nm} \approx H_n$

\[
SPA_{dB} = 20 \log \frac{|F_n\{v_{sub}\}|}{\max\{|F_n\{v_{subm}\}|\}} \approx 20 \log \frac{|F_n\{i\}|}{\max\{|F_n\{i_m\}|\}}
\]
Harmonic balanced plesiochronous design for substrate noise reduction

- Spectral peak attenuation:

$$SPA_{dB} \approx 20 \log \frac{|F_n(i)|}{\max\{|F_n(i_m)|\}}$$
Harmonic balanced plesiochronous design for substrate noise reduction

- Spectral peak attenuation:

\[
SPA_{dB} \approx 20 \log \left( \frac{|F_n(i)|}{\max\{|F_n(i_m)|\}} \right)
\]

- For a synchronous system:

\[
i(t) = \sum_{m=1}^{M} i_m(t) \quad \Rightarrow \quad F_n\{i\} = \sum_{m=1}^{M} F_n\{i_m\}
\]
Harmonic balanced plesiochronous design for substrate noise reduction

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- Also approximately valid for a plesiochronous system
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- Also approximately valid for a plesiochronous system

- Optimal partitioning:

  - Group the blocks into partitions so that the harmonics aimed for reduction be the same for each of the partitions

\[ F_n\{i_1\} = F_n\{i_2\} = \cdots = F_n\{i_M\} = \frac{F_n\{i\}}{M} \quad \Rightarrow \quad \max\{SPA_{dB}\} = 20 \log M \]
Harmonic balanced plesiochronous design for substrate noise reduction

- Spectral peak attenuation:

\[
SPA_{dB} \approx 20 \log \frac{|F_n(i)|}{\max\{|F_n(i_m)|\}}
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\]
The result was obtained by applying an approximation that the differences between the synchronous system frequency and the plesiochronous frequencies are negligible.
Harmonic balanced plesiochronous design for substrate noise reduction

- The result was obtained by applying an approximation that the differences between the synchronous system frequency and the plesiochronous frequencies are negligible.

- Analysis of the impact of that approximation:
  - Switching current modeled as a periodic triangular pulse.
  - Spectrum calculated by applying a nominal frequency, and a frequency with a small offset.
The result was obtained by applying an approximation that the differences between the synchronous system frequency and the plesiochronous frequencies are negligible.

Analysis of the impact of that approximation:
- Switching current modeled as a periodic triangular pulse
- Spectrum calculated by applying a nominal frequency, and a frequency with a small offset

Switching current spectrum envelope

Error in dB, 1% frequency offset

Error in dB, 3% frequency offset

Error in dB, 5% frequency offset
Analysis of the impact of plesiochronous approximation - continuation:

- Harmonic balancing applied at all frequencies, attenuation calculated

Synchronous system – spectrum envelope

Attenuation calculated by applying the plesiochronous approximation

Attenuation calculated without applying the plesiochronous approximation
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Harmonic balanced plesiochronous design in practice

- Finite granularity of the initial synchronous design
  - Design consists of a finite number of blocks
  - Partitioning = Assigning the blocks to partitions
  - Even if suppression at only one harmonic is targeted, possible that the perfect harmonic balancing among partitions can’t be achieved
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Example:
- three blocks
- two partitions
- one harmonic

a b c
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```plaintext
a  b  c  →  a  bc
```
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- It usually happens that perfect balancing of peaks at different harmonics at the same time is not possible

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Example diagram:
```
  a  b  c  a  bc
   ↑   ↑   ⇆   ↑   ↑
```

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Example:
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Example:
- three blocks
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- two harmonics, \( p^{th} \) and \( q^{th} \)
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\[ a \quad b \quad c \quad a \quad bc \]
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- It usually happens that perfect balancing of peaks at different harmonics at the same time is not possible
  
  Example:
  - three blocks
  - two partitions
  - one harmonic

- Find the partitioning which is the closest to the perfect harmonic balancing

Example:
- three blocks
- two partitions
- two harmonics, \( p^{th} \) and \( q^{th} \)
For searching through combinations, the simulated annealing algorithm was used.

Chose initial combination

Example: blocks: a b c d e f g h
initial combination: {a c f h} {b d e g}
Harmonic balanced plesiochronous design in practice

- For searching through combinations, the simulated annealing algorithm was used
  - Chose initial combination
  - Pick a random „neighboring combination“

Example: blocks: a b c d e f g h
initial combination: \{a c f h\} \{b d e g\}
neighboring combination: \{a c h\} \{b d e f g\}
For searching through combinations, the simulated annealing algorithm was used

- Chose initial combination
- Pick a random „neighboring combination“
- If the new combination is better – take it

**Example:**

- **blocks:** \( a \ b \ c \ d \ e \ f \ g \ h \)
- **initial combination:** \{a \ c \ f \ h\} \{b \ d \ e \ g\}
- **neighboring combination:** \{a \ c \ h\} \{b \ d \ e \ f \ g\}
For searching through combinations, the simulated annealing algorithm was used

- Chose initial combination
- Pick a random „neighboring combination“
- If the new combination is better – take it
- If the new combination is worse – take it only with some probability, which gets smaller with the number of iterations

Example:

blocks: $a \ b \ c \ d \ e \ f \ g \ h$

initial combination: $\{a \ c \ f \ h\} \ \{b \ d \ e \ g\}$

neighboring combination: $\{a \ c \ h\} \ \{b \ d \ e \ f \ g\}$
Harmonic balanced plesiochronous design in practice

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  - Chose initial combination
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- Cost function to decide whether the combination is better or worse
  - Least total harmonics power
  - Least mean square difference to the theoretically „perfect partitioning“
  - Least power of the strongest harmonic

Example: blocks: a b c d e f g h
initial combination: \{a c f h\} \{b d e g\}
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  - Least mean square difference to the theoretically „perfect partitioning“
  - Least power of the strongest harmonic

- Calculate the cost function only for the frequency band(s) targeted for optimization
  → Frequency selective attenuation

Example: blocks: \( a b c d e f g h \)
initial combination: \{a c f h\} \{b d e g\}
neighboring combination: \{a c h\} \{b d e f g\}
Harmonic balanced plesiochronous design in practice

- initial partitioning, cost function: \( c_{old} \)
- neighboring partitioning, cost function: \( c_{new} \)

\[\begin{align*}
\text{IF } c_{new} < c_{old} : & \quad a_p = e^{-\frac{c_{new} - c_{old}}{T}} \\
\text{ELSE } \quad a_p = 1 : & \\
\text{IF } a_p \geq \text{rand} : & \\
\text{YES } \quad \text{assign the new partitioning } \quad \text{old} \leftarrow \text{new} & \\
\text{ELSE :} & \\
\text{NO } & \\
\text{convergence?} & \\
\text{IF } \text{convergence} : & \\
\text{YES } \quad \text{finish} & \\
\text{ELSE :} & \\
\text{NO } & \\
\end{align*}\]

Notes:
- \( a_p \) – acceptance probability of the new partitioning
- \( T \) – “temperature”, a parameter which gets reduced at each iteration
- \( 0 \leq \text{rand} \leq 1 \)
- \( \alpha < 1 \)
Harmonic balanced plesiochronous design in practice

current profiles of blocks

initial partitioning, cost function: $c_{old}$

neighboring partitioning, cost function: $c_{new}$

- If $c_{new} < c_{old}$:
  - $a_p = 1$
  - $a_p = e^{-\frac{(c_{new} - c_{old})}{T}}$

- If $a_p \geq \text{rand}$:
  - assign the new partitioning
    - $old \leftarrow new$

- If $T = \alpha T$:
  - convergence?

Notes:
- $a_p$ – acceptance probability of the new partitioning
- $T$ – “temperature”, a parameter which gets reduced at each iteration
  - $0 \leq \text{rand} \leq 1$
  - $\alpha < 1$
Harmonic balanced plesiochronous design in practice

![Diagram of the harmonic balanced plesiochronous design process]

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- $0 \leq \text{rand} \leq 1$
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Harmonic balanced plesiochronous design
in practice

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- $T$ – “temperature”, a parameter which gets reduced at each iteration
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  $\alpha < 1$

current profiles of blocks

initial partitioning, cost function: $c_{\text{old}}$

neighboring partitioning, cost function: $c_{\text{new}}$

$\begin{align*}
\text{YES} & \quad \frac{c_{\text{new}}}{c_{\text{old}}} < 1 \\
\text{NO} & \quad a_p = e^{-\frac{c_{\text{new}}-c_{\text{old}}}{T}}
\end{align*}$

$\begin{align*}
a_p & \geq \text{rand} \\
\text{YES} & \quad \text{assign the new partitioning} \\
& \quad old \leftarrow \text{new}
\end{align*}$

$\begin{align*}
T & = \alpha T \\
\text{NO} & \quad \text{convergence?}
\end{align*}$

$\begin{align*}
\text{YES} & \quad \text{finish}
\end{align*}$
Harmonic balanced plesiochronous design in practice

1. initial partitioning, cost function: $c_{old}$
2. neighboring partitioning, cost function: $c_{new}$

- $c_{new} < c_{old}$
  - $a_p = 1$
  - $a_p = e^{-\frac{(c_{new} - c_{old})}{T}}$

- $a_p \geq \text{rand}$
  - assign the new partitioning
    - $old \leftarrow new$
    - $T = \alpha T$

- convergence?
  - NO
  - $T = \alpha T$
  - YES
    - finish

Notes:
- $a_p$ – acceptance probability of the new partitioning
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Notes:
- $a_p$ – acceptance probability of the new partitioning
- $T$ – “temperature”, a parameter which gets reduced at each iteration
- $0 \leq \text{rand} \leq 1$
- $\alpha < 1$
Numerical evaluation of the methodology in MATLAB

- Block waveforms: periodic triangular pulses
- Random rise times (range: 0-20% $T_{sclk}$) and fall times (range: 0-80% $T_{sclk}$)
- Random current peak (range: 0 - 1 mA)
- 40 blocks, 5 partitions (theoretically maximum attenuation: 13.98 dB)
- Frequency offsets for the partitions: -4%, -2%, 1%, 3%, 5%
Numerical evaluation of the methodology in MATLAB

- Block waveforms: periodic triangular pulses
- Random rise times (range: 0-20% $T_{sclk}$) and fall times (range: 0-80% $T_{sclk}$)
- Random current peak (range: 0 - 1 mA)
- 40 blocks, 5 partitions (theoretically maximum attenuation: 13.98 dB)
- Frequency offsets for the partitions: -4%, -2%, 1%, 3%, 5%

- Optimization on all the harmonics:

```
spectrum envelopes:
red dotted – synchronous
red – GALS, “perfect” partitioning
green – GALS
```

```
spectral peak attenuation
```

```
Numerical evaluation of the methodology in MATLAB

- Optimization in [1.5 GHz – 2.5 GHz] frequency band:

  - spectrum envelopes:
    - red dotted – synchronous
    - red – GALS, “perfect” partitioning
    - green – GALS

  - spectral peak attenuation
Numerical evaluation of the methodology in MATLAB

- Optimization in [5 GHz – 5.5 GHz] frequency band:

  spectrum envelopes:
  red dotted – synchronous
  red – GALS, “perfect” partitioning
  green – GALS

  spectral peak attenuation
Numerical evaluation of the methodology in MATLAB

- Optimization in [1.5 GHz – 2.5 GHz] and [5 GHz – 5.5 GHz] frequency bands:

  spectrum envelopes:
  - red dotted – synchronous
  - red – GALS, “perfect” partitioning
  - green – GALS

  spectral peak attenuation
Agenda

1. Introduction
2. Switching current spectrum optimization requirements for substrate noise reduction
3. Harmonic balanced partitioning
4. GALS partitioning algorithm for substrate noise reduction
5. Methodology for GALS partitioning
6. Conclusions and future work
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Application on a realistic design example

- Intended for use as a part of wireless sensor network
- LEON2 32-bit microprocessor and three accelerator cores for cryptographic operations (SHA-1, AES and ECC)
- Hierarchical netlist: 21 block
- Optimization bands:
  - The first harmonic (50 MHz) and GSM-850 band (800 MHz, 850 MHz, 900 MHz)
- 5 LSMs, frequency offsets: 2.56%, 1.26%, 0%, -1.24% and -2.44%
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  - ~7 dB for the strongest components, less for the weaker components

![Graph showing synchronous system](image)
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![GALS system graph]
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- A GALS methodology for substrate noise reduction presented, based on harmonic balanced partitioning scheme
  - Use switching current profiles of design subcomponents
  - Calculate the spectra
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- Future work
  - Further automatization of the implemented low noise methodology
    - Automate the asynchronous wrapper integration phase
  - Fabricate a test chip to demonstrate the methodology
Thank you for your attention!

Babić, Milan

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Appendix 1: Partitioning of the design example

Table I. Harmonic peaks and harmonic power attenuations in dB

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- Ground bounce $\rightarrow$ Voltage fluctuations in the substrate (substrate noise)
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- Ground bounce $\rightarrow$ Voltage fluctuations in the substrate (substrate noise)

- Injection to analog circuits
  - Direct injection through substrate contacts
  - Body effect
  - Capacitive coupling through S/D junction capacitances

- This noise further propagates to the outputs of analog circuits, impacting the performance
Appendix 3: Harmonic balanced plesiochronous design in practice

Notes:
- \( a_p \) – acceptance probability of the new partitioning
- \( T \) – “temperature”, a parameter which gets reduced at each iteration
  - \( 0 \leq \text{rand} \leq 1 \)
  - \( \alpha < 1 \)

Probabilistic – doesn’t always output the same combinations, especially if many combinations have a similar value of cost function
Appendix 4: Harmonic balanced plesiochronous design for substrate noise reduction

- Spectral peak attenuation:

\[ i(t) = \sum_{m=1}^{M} i_m(t) \quad \Rightarrow \quad F_n\{i\} = \sum_{m=1}^{M} F_n\{i_m\} \]

\[ F_n\{i\} \text{ – } n^{th} \text{ harmonic of the switching current spectrum for the synchronous system} \]

\[ F_n\{i_m\} \text{ – } n^{th} \text{ harmonic of the switching current spectrum for the } m^{th} \text{ partition of the system} \]

valid for a synchronous design, approximately also valid for a plesiochronous design
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\[ H_{n1} \approx H_{n2} \approx ... \approx H_{nM} \approx H_n \]

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- **\( H_n \) – the value of substrate transfer function at the frequency of the synchronous system**
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- Group the blocks into partitions so that the harmonics aimed for reduction be the same for each of the partitions

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