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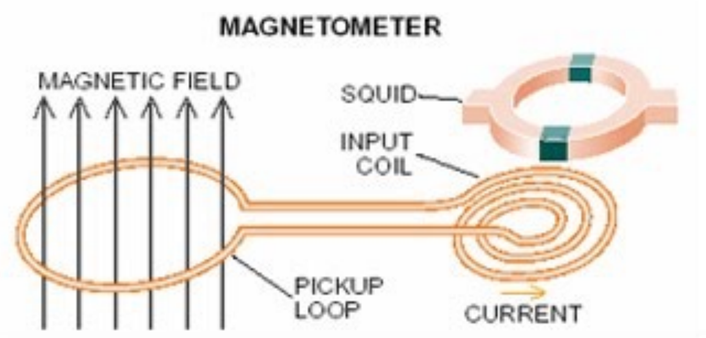
ASC 22

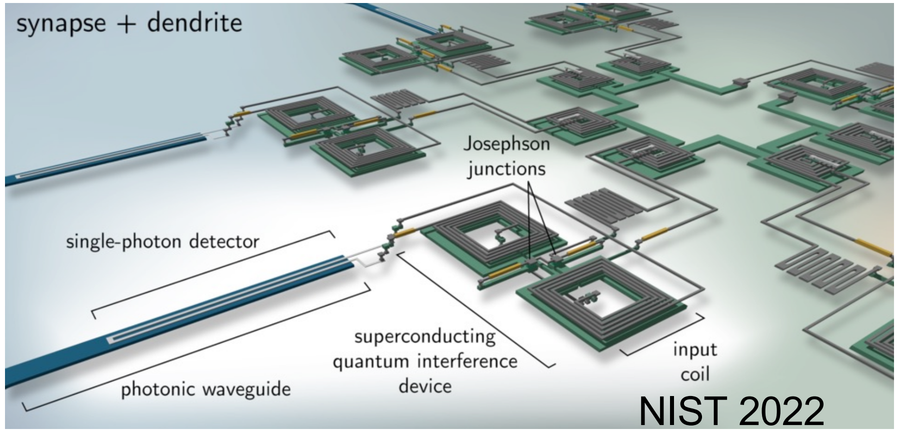
# Low-Cost Fan-Out with SFQ Cell Labeling

**Jennifer Volk,**
George Tzimpragos,
Alex Wynn,
Evan Golden,
Tim Sherwood

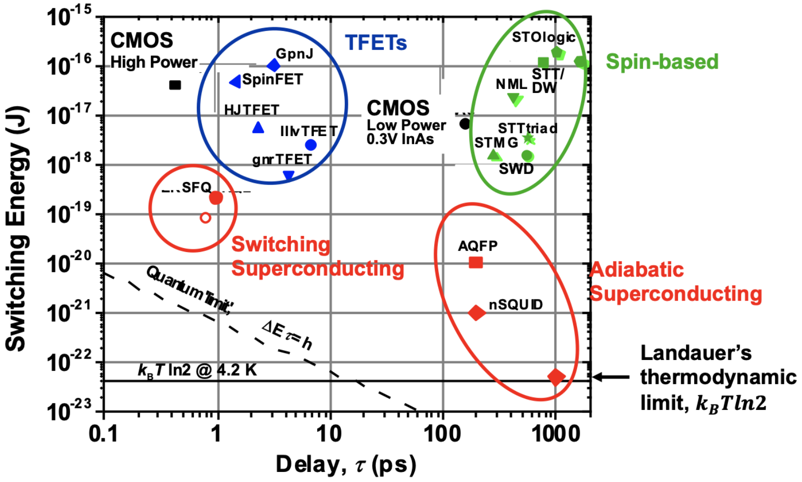
UNIVERSITY OF MICHIGAN
LINCOLN LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
UC SANTA BARBARA

# The Beauty…

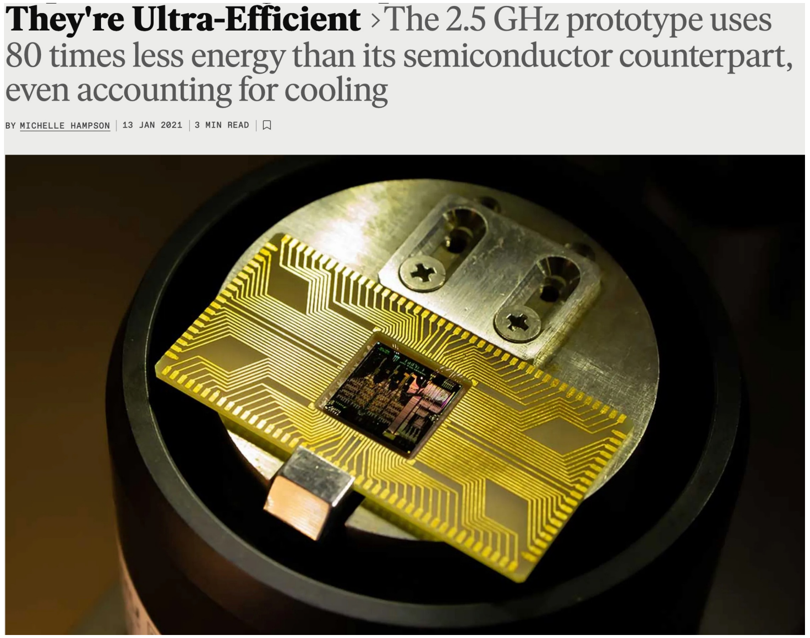




Ultralow Logic Energy and High Speed

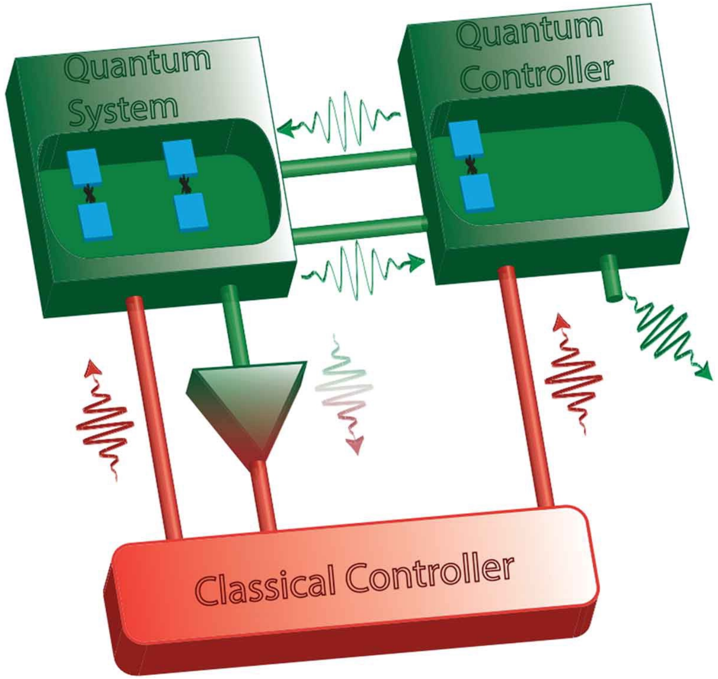


L. Johnson



**They're Ultra-Efficient** ›The 2.5 GHz prototype uses 80 times less energy than its semiconductor counterpart, even accounting for cooling

BY MICHELLE HAMPSON | 13 JAN 2021 | 3 MIN READ



## Method 1: device

L. Johnson, 2018
S. Tolpygo, 2020
I. I. Soloviev, 2021
O. Mukhanov, 1997
S. Tolpygo, 2020
O. Mukhanov, 2011
A. Kadin, 2001
J. Kang, 2003
B. Dimov, 2005
M. Maezawa, 2007
M. Suzuki, 2004
B. Ebert, 2009
N. Yoshikawa, 1999
L. Schindler, 2021
S. Tolpygo, 2007
V. Semenov, 2021
S. Tolpygo, 2019
T. Ortlepp, 2007
V. Kaplunenko, 1995
D. Brock, 2001
L. Gronberg, 2007
I. Vernik, 1999
D. Balashov, 1999
T. Wolf, 2013

## Method 2: EDA

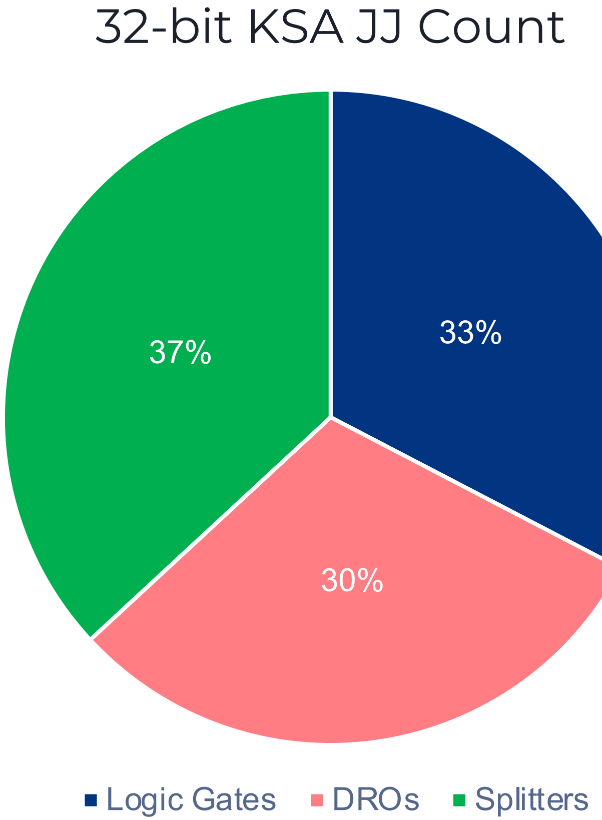
G. Pasandi, 2018
N. Yoshikawa, 2001
K. Gaj, 1997
C. Fourie, 2020
I. Byun, 2022
H. Gerber, 2005
A. Haslam, 2018
A. Krasniewski, 1993
K. Gaj, 1999
K. Gaj, 1997
V. Adler, 1997
D. Brock, 1997
C. Fourie, 2012
R. Koch, 1997
R.M.C. Roberts, 2014
A. Haslam, 2019
L. Müller, 2013
C. Fourie, 2018
R. Tadros, 2019
A. Inamdar, 2021
N. Kito, 2019
T. Jabbari, 2020
S. Lo, 2022
R. Fu, 2021

## Method 3: architecture

A. Fujimaki, 2014
G. Tzimpragos, 2019
G. Tzimpragos, 2020
G. Tzimpragos, 2021
J. Volk, 2022
M. Dorojevets, 2013
F. Zokaee, 2021
C. Fourie, 2020
M. Dorojevets, 2003
K. Gaj, 1995
P. Bunyk, 1997
D. Brock, 2001
R. Tadros, 2017
D. Zinoviev, 1998
F. Feldhoff, 2021
P. Bunyk, 1995
M. Dorojevets, 2010
H. Gerber, 2007
Z. Deng, 1997
M. Dorojevets, 1999
N. Takagi, 2008
K. Ishida, 2020
C. Ayala, 2020
Y. Ando, 2016
M. Tanaka, 2015

## Method 4: JJ utility

# Breakdown & challenge



H. Cong, 2021

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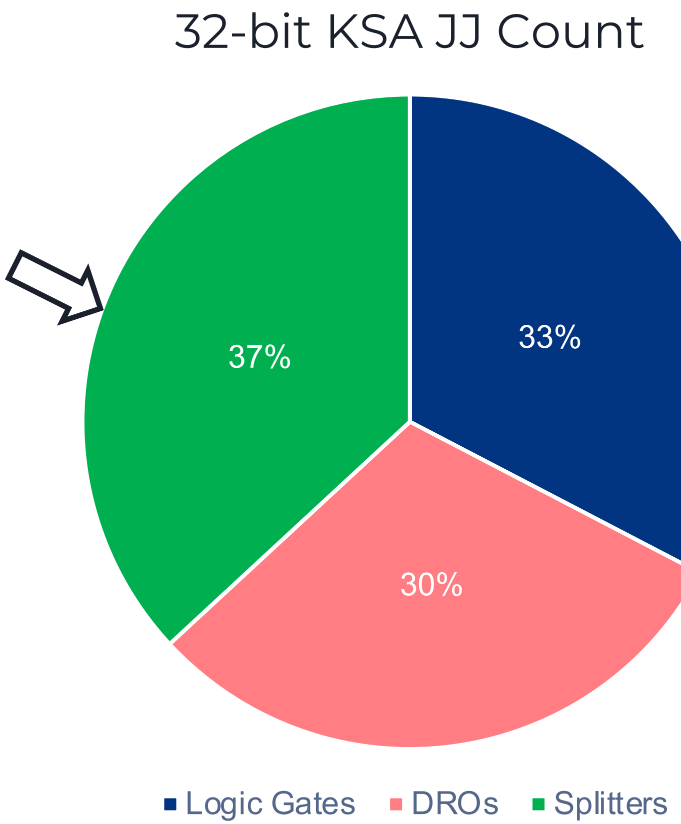
# Breakdown & challenge



H. Cong, 2021

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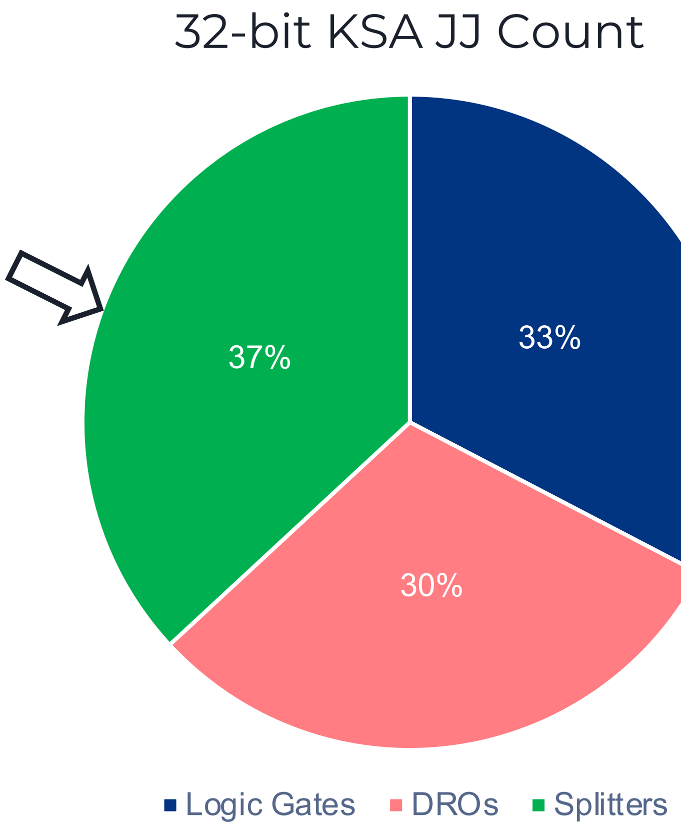
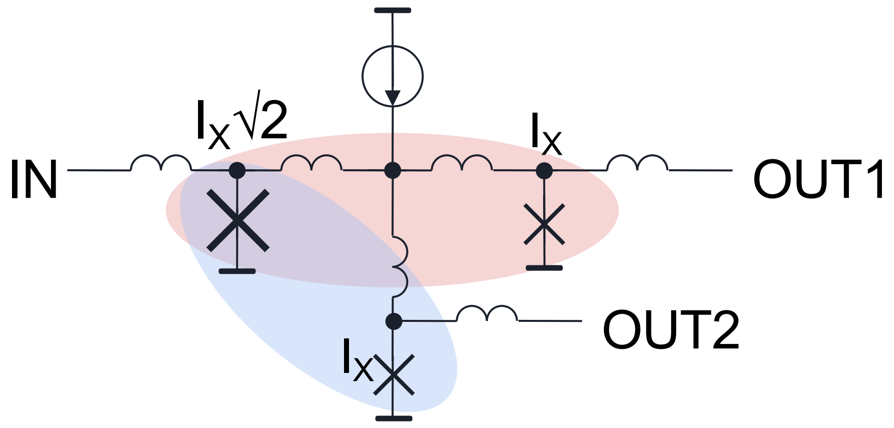
# Breakdown & challenge



H. Cong, 2021

🟨 Splitter



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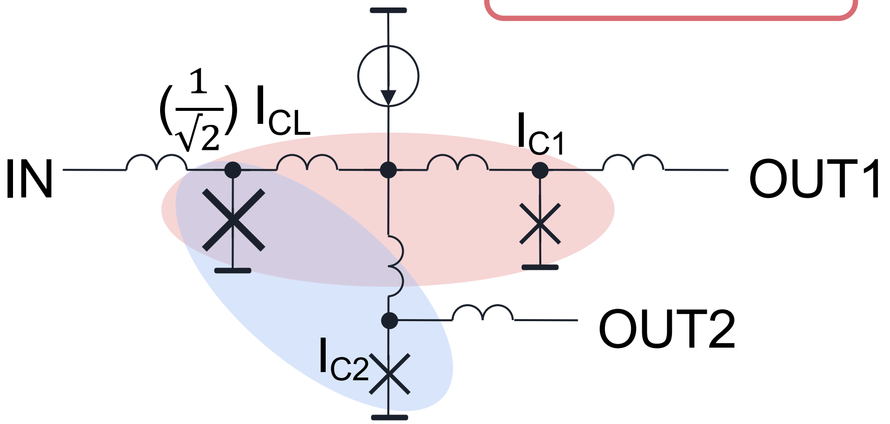
# This looks familiar...

🟨 Splitter

$I_{CL} = I_{C1} + I_{C2}$



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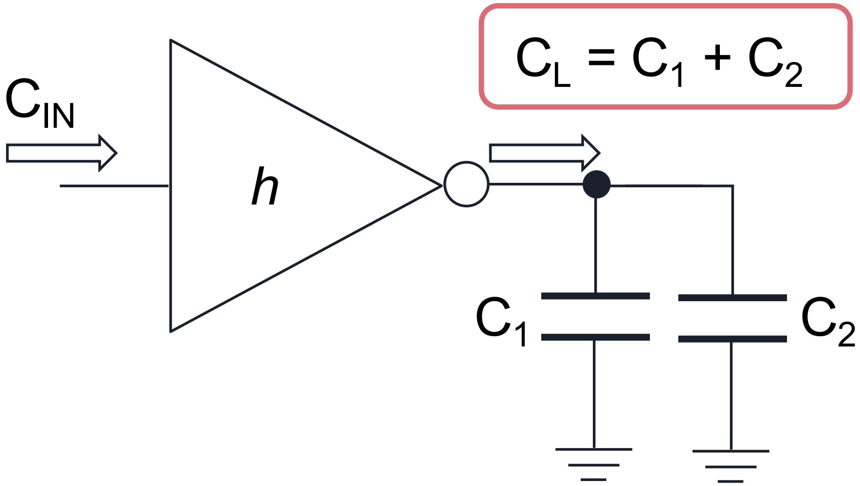
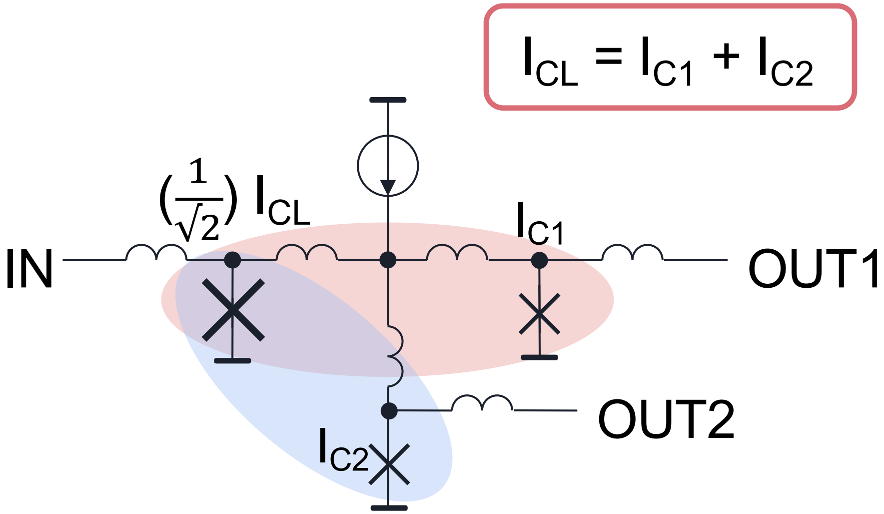
# This looks familiar…

## Electrical Effort



## Splitter



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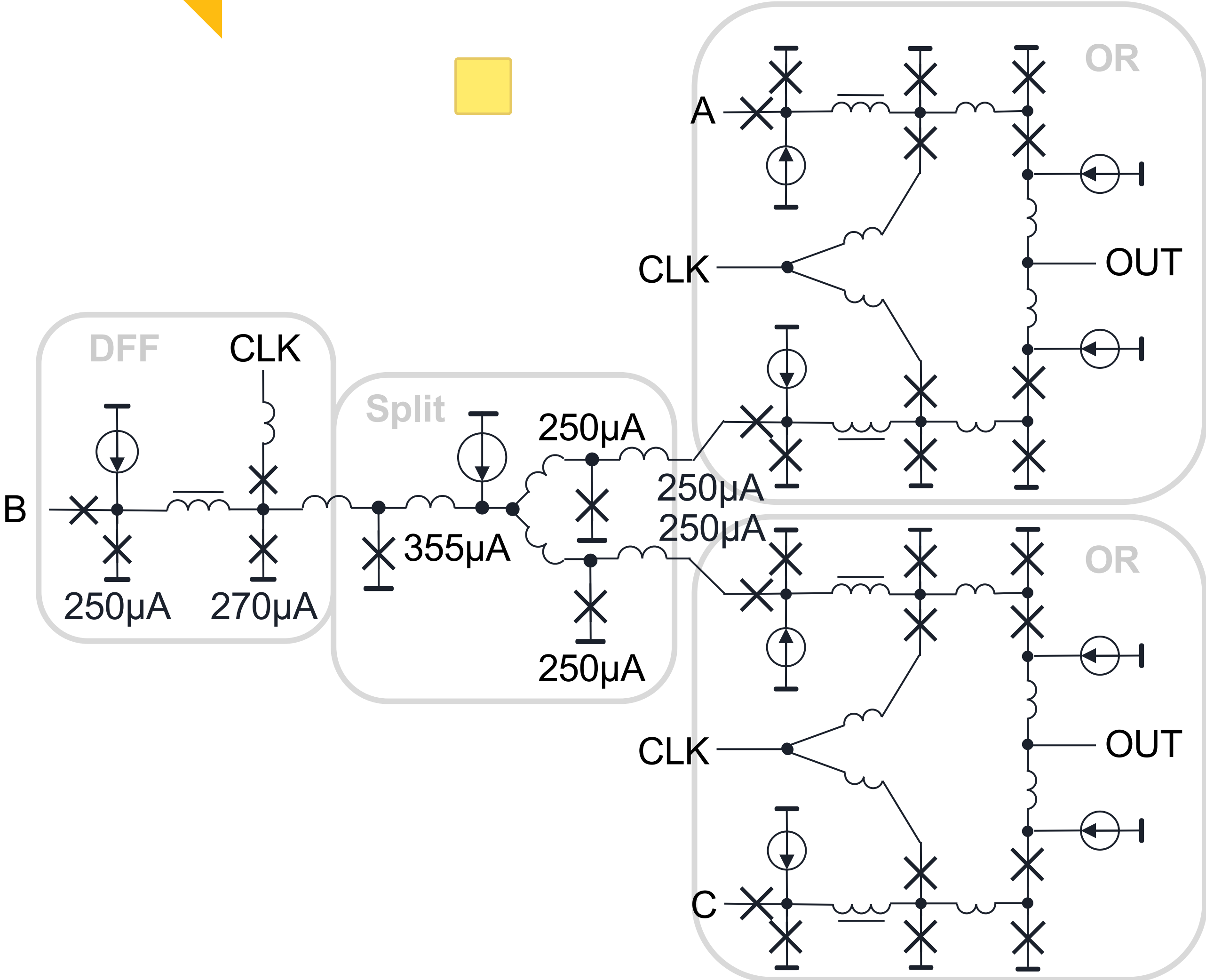
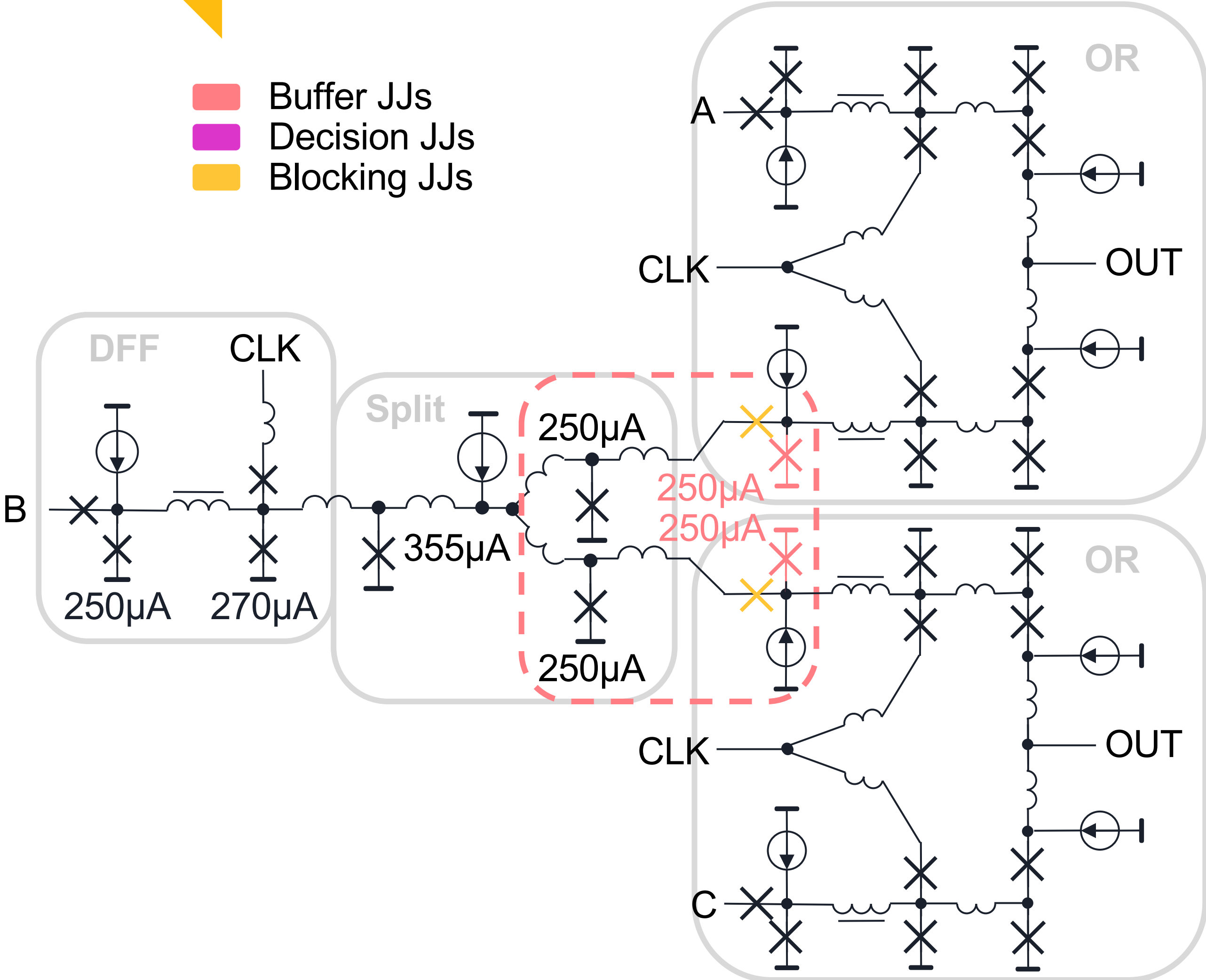
# Reducing Redundancies: JJ Borrowing



# Reducing Redundancies: JJ Borrowing

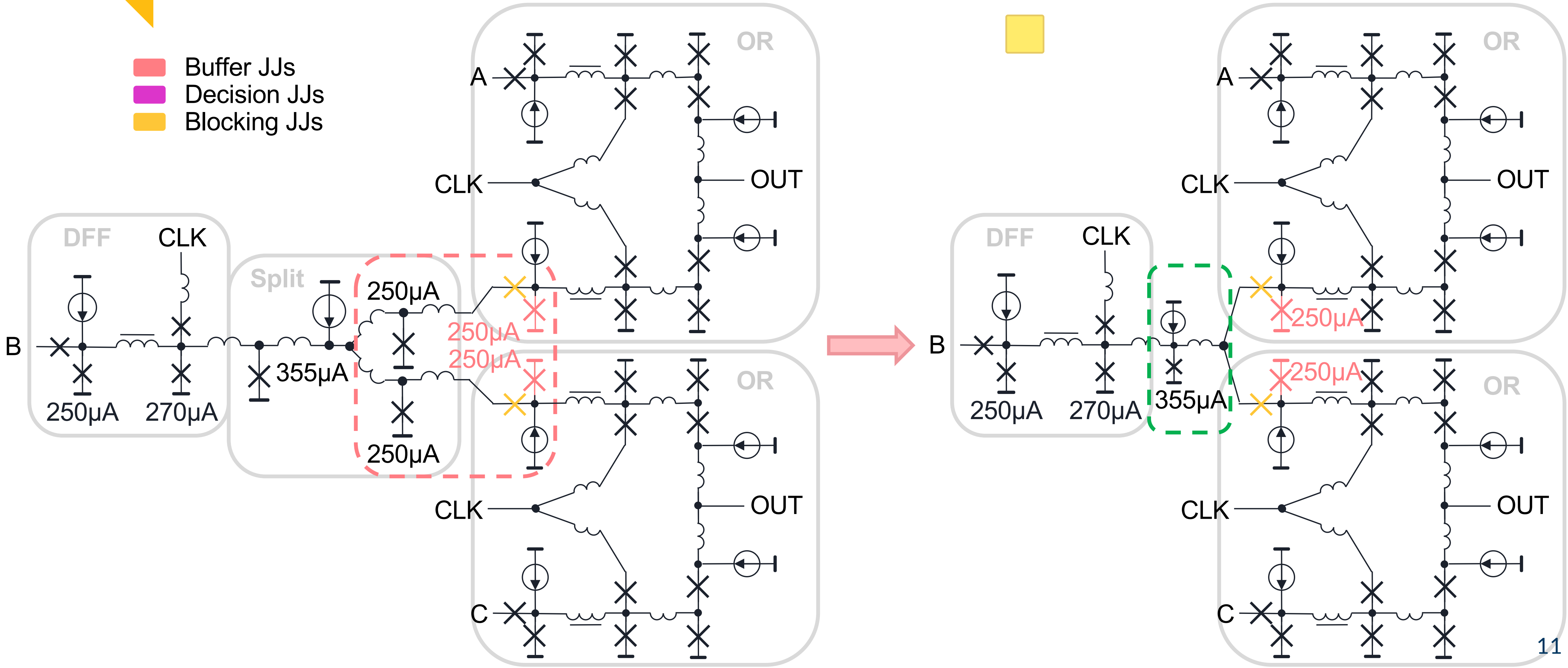
UCSB

- 🟥 Buffer JJs
- 🟪 Decision JJs
- 🟨 Blocking JJs

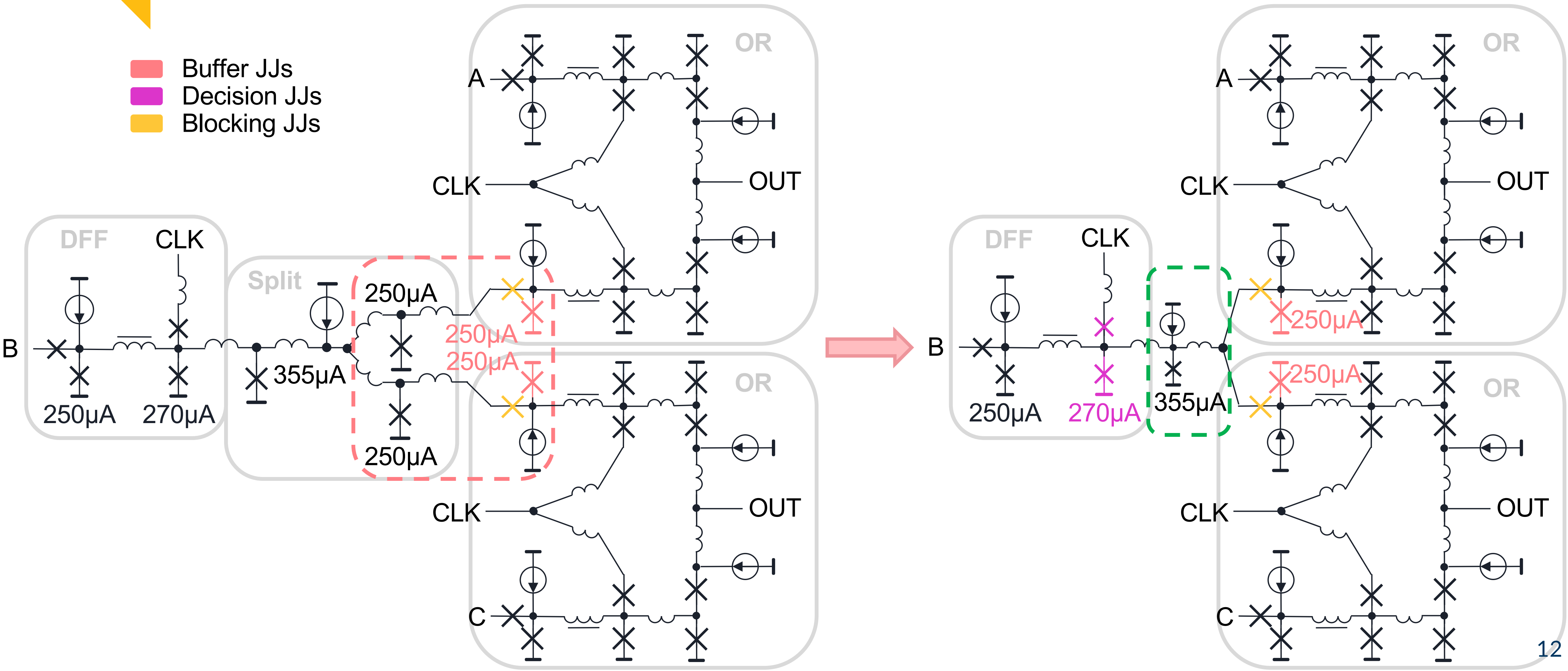


# Reducing Redundancies: JJ Borrowing

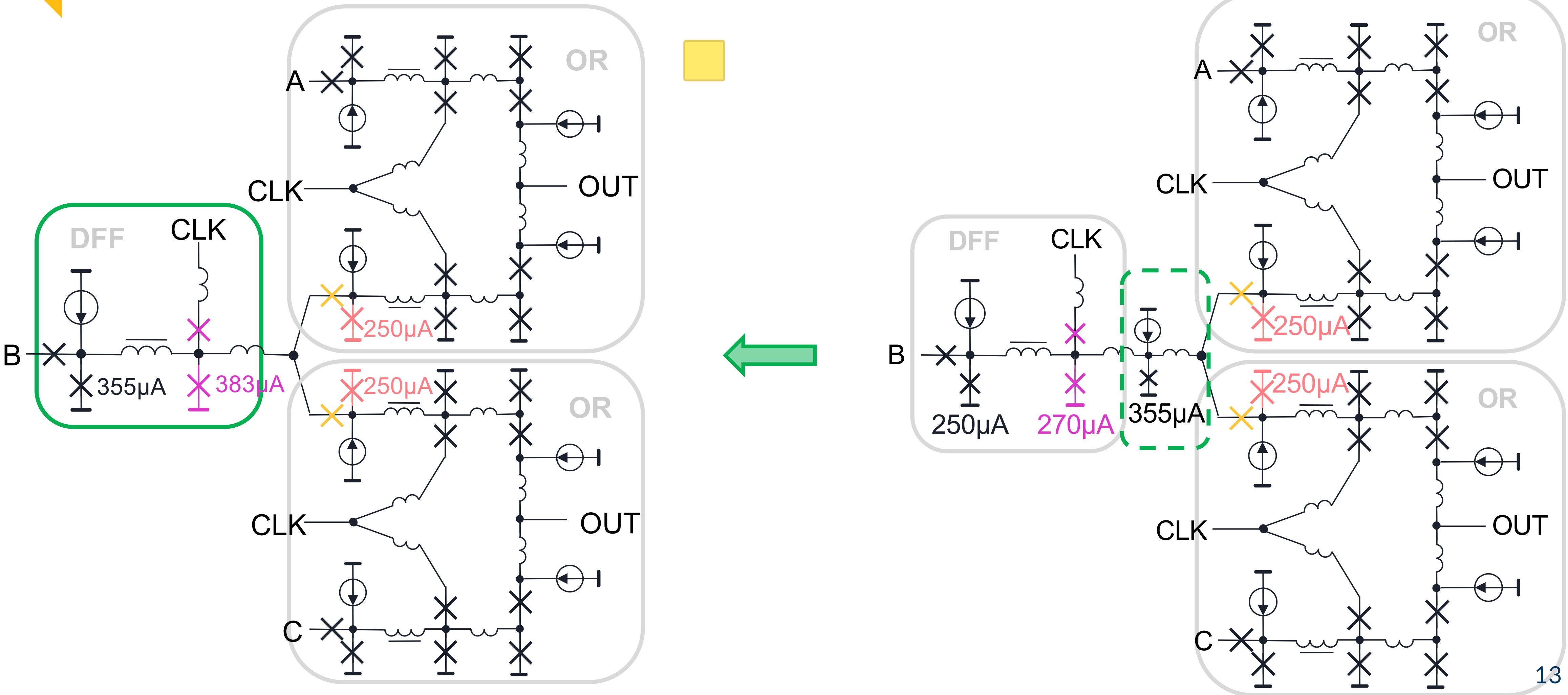
- 🟥 Buffer JJs
- 🟪 Decision JJs
- 🟨 Blocking JJs



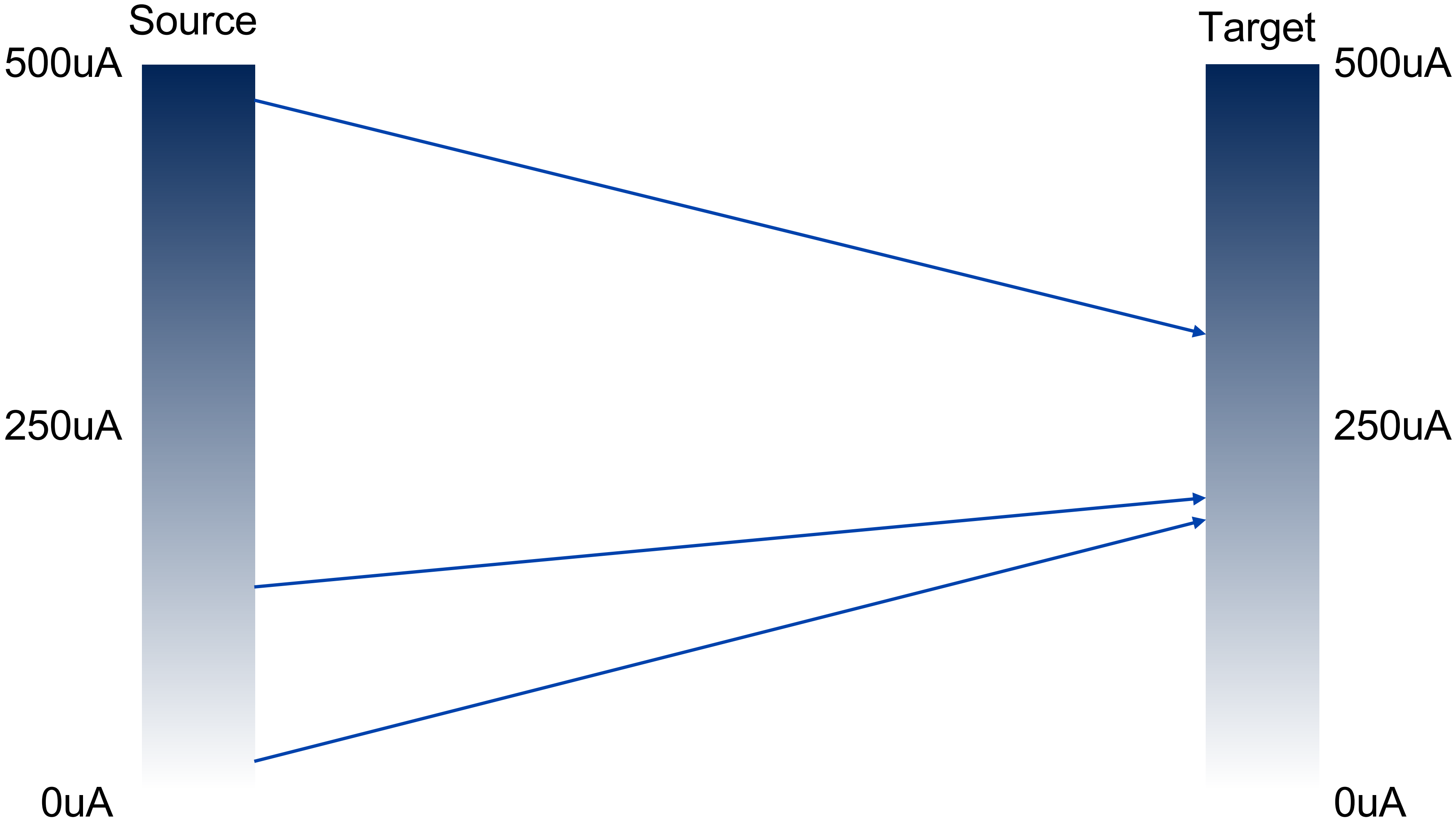
# Reducing Redundancies: JJ Borrowing



# Reducing Redundancies: JJ Borrowing



# Generalizing Connectivity Rules



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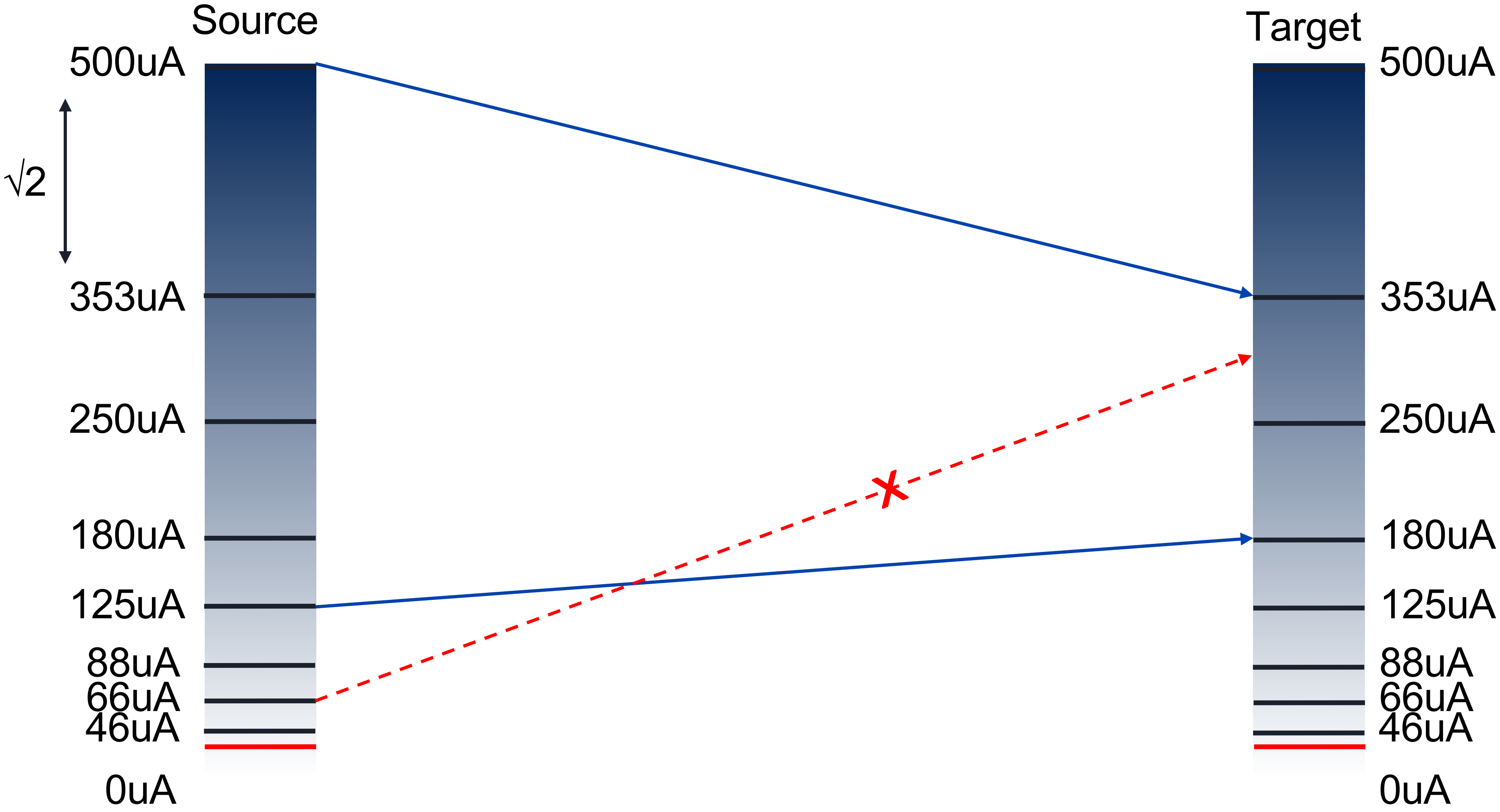
# Generalizing Connectivity Rules



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# Generalizing Connectivity Rules

Target

Source

| $I_C$ | 500μA | 353μA | 250μA | 180μA | 125μA | 88μA | 66μA | 46μA |
|---|---|---|---|---|---|---|---|---|
| 500μA | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 |
| 353μA |  | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 |
| 250μA |  |  | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 |
| 180μA |  |  |  | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 |
| 125μA |  |  |  |  | 🟩 | 🟩 | 🟩 | 🟩 |
| 88μA |  |  |  |  |  | 🟩 | 🟩 | 🟩 |
| 66μA |  |  |  |  |  |  | 🟩 | 🟩 |
| 46μA |  |  |  |  |  |  |  | 🟩 |

# Generalizing Connectivity Rules

**Target**

**Source**

| $I_C$ | 500μA | 353μA | 250μA | 180μA | 125μA | 88μA | 66μA | 46μA |
|---|---|---|---|---|---|---|---|---|
| **500μA** | FO1 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 |
| **353μA** | | FO1 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 |
| **250μA** | | | FO1 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 |
| **180μA** | | | | FO1 | 🟩 | 🟩 | 🟩 | 🟩 |
| **125μA** | | | | | FO1 | 🟩 | 🟩 | 🟩 |
| **88μA** | | | | | | FO1 | 🟩 | 🟩 |
| **66μA** | | | | | | | FO1 | 🟩 |
| **46μA** | | | | | | | | FO1 |

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# Generalizing Connectivity Rules

Target

Source

| $I_C$ | 500µA | 353µA | 250µA | 180µA | 125µA | 88µA | 66µA | 46µA |
|---|---|---|---|---|---|---|---|---|
| **500µA** | FO1 | FO2 | FO3 | FO4 | FO5 | FO6 | FO7 | FO8 |
| **353µA** |  | FO1 | FO2 | FO3 | FO4 | FO5 | FO6 | FO7 |
| **250µA** |  |  | FO1 | FO2 | FO3 | FO4 | FO5 | FO6 |
| **180µA** |  |  |  | FO1 | FO2 | FO3 | FO4 | FO5 |
| **125µA** |  |  |  |  | FO1 | FO2 | FO3 | FO4 |
| **88µA** |  |  |  |  |  | FO1 | FO2 | FO3 |
| **66µA** |  |  |  |  |  |  | FO1 | FO2 |
| **46µA** |  |  |  |  |  |  |  | FO1 |

Amplification

UCSB

# Generalizing Connectivity Rules

**Target**

**Source**

| $I_C$ | 500μA | 353μA | 250μA | 180μA | 125μA | 88μA | 66μA | 46μA |
|---|---|---|---|---|---|---|---|---|
| **500μA** | FO1 | FO2 | FO3 | FO4 | FO5 | FO6 | FO7 | FO8 |
| **353μA** | | FO1 | FO2 | FO3 | FO4 | FO5 | FO6 | FO7 |
| **250μA** | | | FO1 | FO2 | FO3 | FO4 | FO5 | FO6 |
| **180μA** | | | | FO1 | FO2 | FO3 | FO4 | FO5 |
| **125μA** | | | | | FO1 | FO2 | FO3 | FO4 |
| | | | | | | FO1 | FO2 | FO3 |
| | | | | | | | FO1 | FO2 |
| **46μA** | | | | | | | | FO1 |

$$N_{JTL} \geq \frac{\log\left(\frac{I_T}{I_S}\right)}{\log(p_r)}$$

Amplification

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# Generalizing Connectivity Rules

Target

Source

| $I_C$ | 500µA | 353µA | 250µA | 180µA | 125µA | 88µA | 66µA | 46µA |
|---|---|---|---|---|---|---|---|---|
| **500µA** | FO1 | FO2 | FO3 | FO4 | FO5 | FO6 | FO7 | FO8 |
| **353µA** | +1 JTL | FO1 | FO2 | FO3 | FO4 | FO5 | FO6 | FO7 |
| **250µA** | +2 JTL | +1 JTL | FO1 | FO2 | FO3 | FO4 | FO5 | FO6 |
| **180µA** | +2 JTL | +2 JTL | +1 JTL | FO1 | FO2 | FO3 | FO4 | FO5 |
| **125µA** | +3 JTL | +2 JTL | +2 JTL | +1 JTL | FO1 | FO2 | FO3 | FO4 |
| [illegible] | +3 JTL | +3 JTL | +2 JTL | +2 JTL | +1 JTL | FO1 | FO2 | FO3 |
| [illegible] | +4 JTL | +3 JTL | +3 JTL | +2 JTL | +2 JTL | +1 JTL | FO1 | FO2 |
| **46µA** | +4 JTL | +4 JTL | +3 JTL | +3 JTL | +2 JTL | +2 JTL | +1 JTL | FO1 |

$$N_{JTL} \geq \frac{\log\left(\frac{I_T}{I_S}\right)}{\log(p_r)}$$

Amplification

UCSB

# Generalizing Connectivity Rules

**Target**

**Source**

| | **Rank** | **8** | **7** | **6** | **5** | **4** | **3** | **2** | **1** |
|---|---|---|---|---|---|---|---|---|---|
| **Rank** | **$I_C$** | **500μA** | **353μA** | **250μA** | **180μA** | **125μA** | **88μA** | **66μA** | **46μA** |
| **8** | **500μA** | FO1 | FO2 | FO3 | FO4 | FO5 | FO6 | FO7 | FO8 |
| **7** | **353μA** | +1 JTL | FO1 | FO2 | FO3 | FO4 | FO5 | FO6 | FO7 |
| **6** | **250μA** | +2 JTL | +1 JTL | FO1 | FO2 | FO3 | FO4 | FO5 | FO6 |
| **5** | **180μA** | +2 JTL | +2 JTL | +1 JTL | FO1 | FO2 | FO3 | FO4 | FO5 |
| **4** | **125μA** | +3 JTL | +2 JTL | +2 JTL | +1 JTL | FO1 | FO2 | FO3 | FO4 |
| **3** | **88μA** | +3 JTL | +3 JTL | +2 JTL | +2 JTL | +1 JTL | FO1 | FO2 | FO3 |
| **2** | **66μA** | +4 JTL | +3 JTL | +3 JTL | +2 JTL | +2 JTL | +1 JTL | FO1 | FO2 |
| **1** | **46μA** | +4 JTL | +4 JTL | +3 JTL | +3 JTL | +2 JTL | +2 JTL | +1 JTL | FO1 |

Amplification

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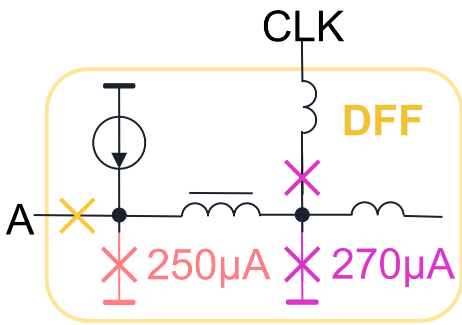
# Design Methodology

## 1. All logic cells have same rank

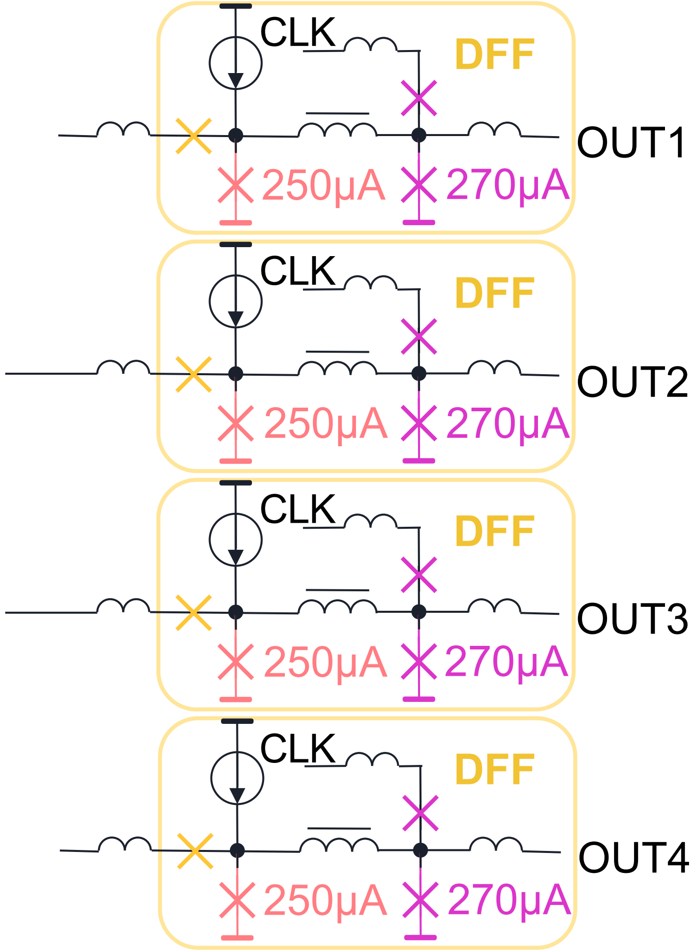


Rank-6

Target

Source

| | Rank | 7 | 6 |
|---|---|---|---|
| Rank | $I_C$ | 353μA | 250μA |
| 7 | 353μA | FO1 | FO2 |



Rank-6

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# Design Methodology

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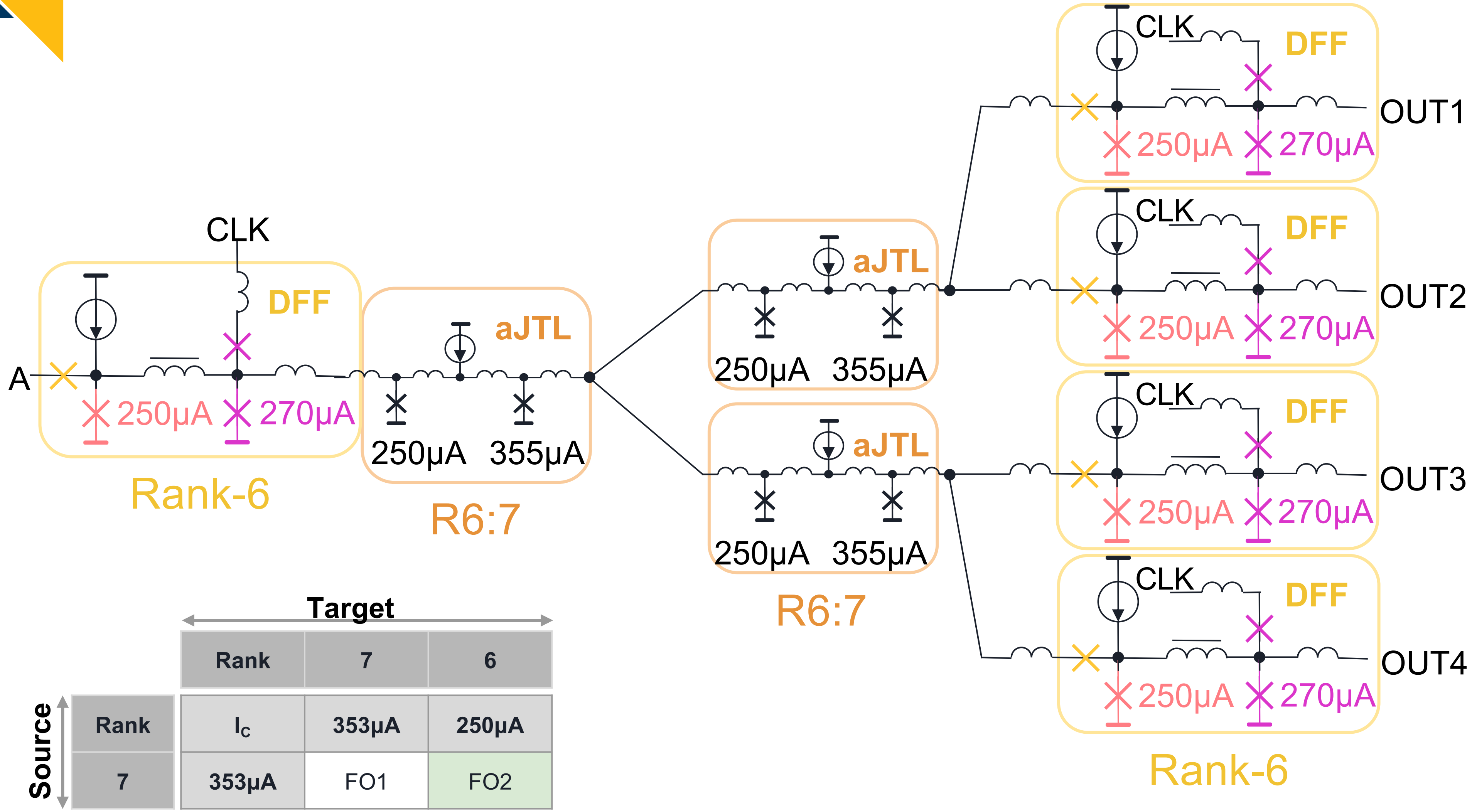

**Target**

**Source**

| | **Rank** | **7** | **6** |
|---|---|---|---|
| **Rank** | **I$_C$** | **353µA** | **250µA** |
| **7** | **353µA** | FO1 | FO2 |

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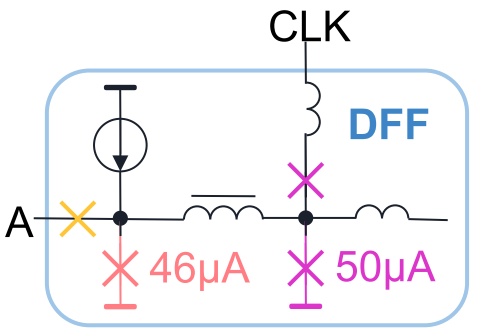
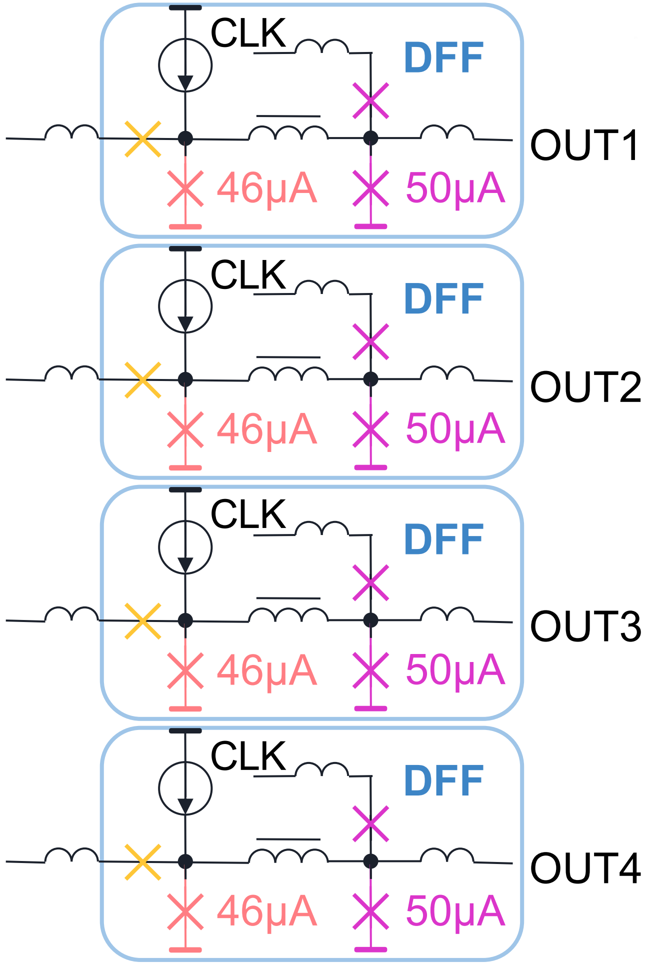
# Design Methodology

## 2. All logic cells have lowest rank



Rank-1

|  |  |  | Target |  |
|---|---|---|---|---|
|  |  | Rank | 4 | 1 |
| Source | Rank | $I_C$ | 125µA | 46µA |
|  | 4 | 125µA | FO1 | FO4 |
|  | 1 | 46µA | +2 JTL | FO1 |



Rank-1

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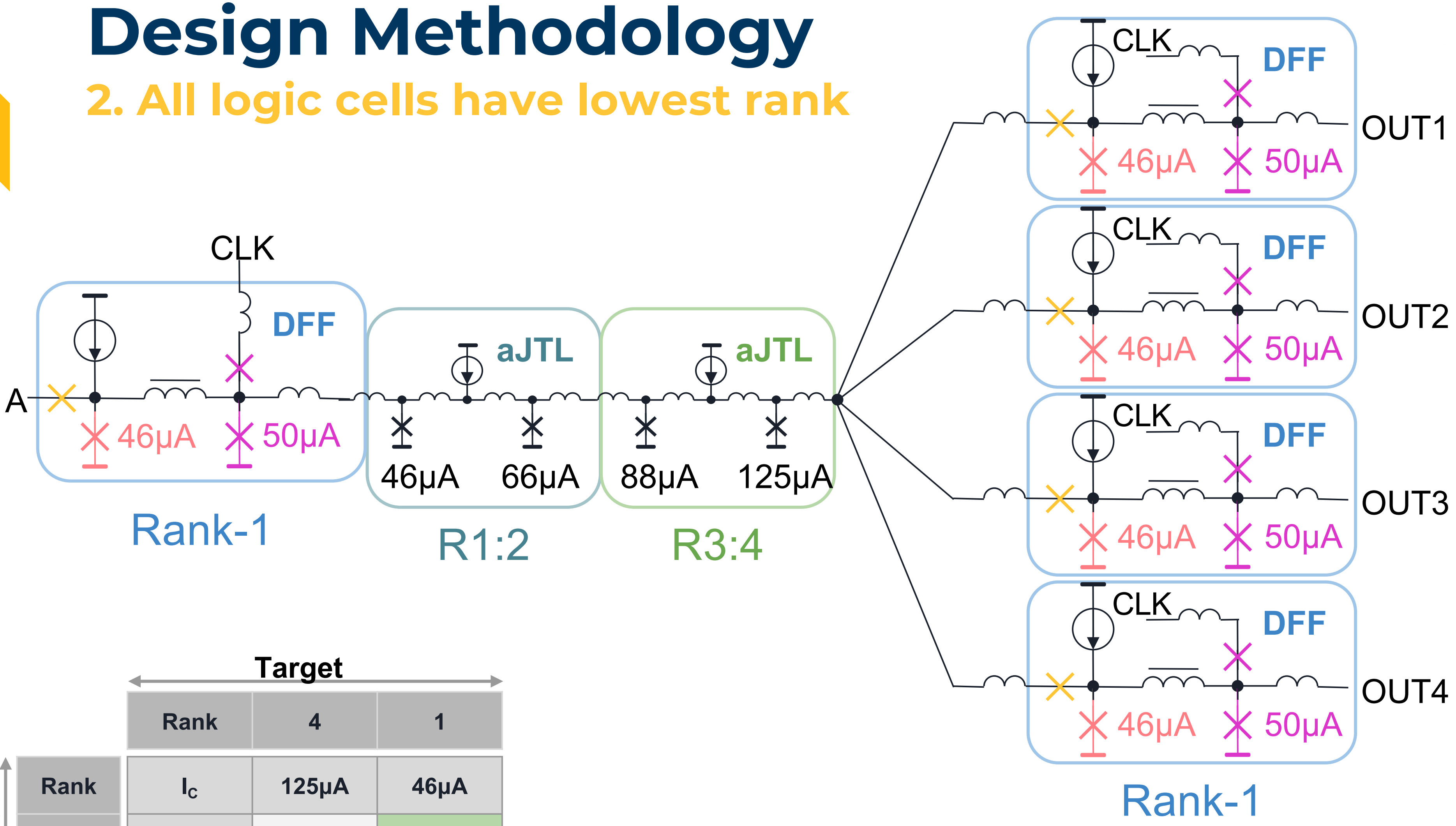
# Design Methodology

## 2. All logic cells have lowest rank



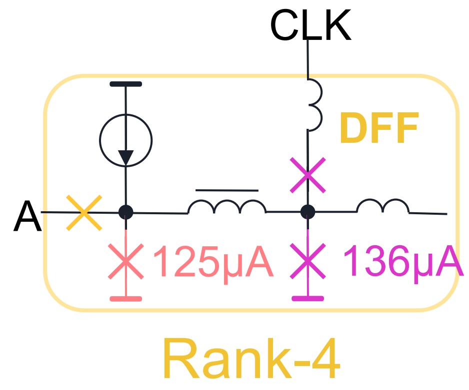
Target

Source

| | | | |
|---|---|---|---|
| | **Rank** | **4** | **1** |
| **Rank** | **$I_C$** | **125µA** | **46µA** |
| **4** | **125µA** | FO1 | FO4 |
| **1** | **46µA** | +2 JTL | FO1 |

# Design Methodology

## 3. Flexible rank



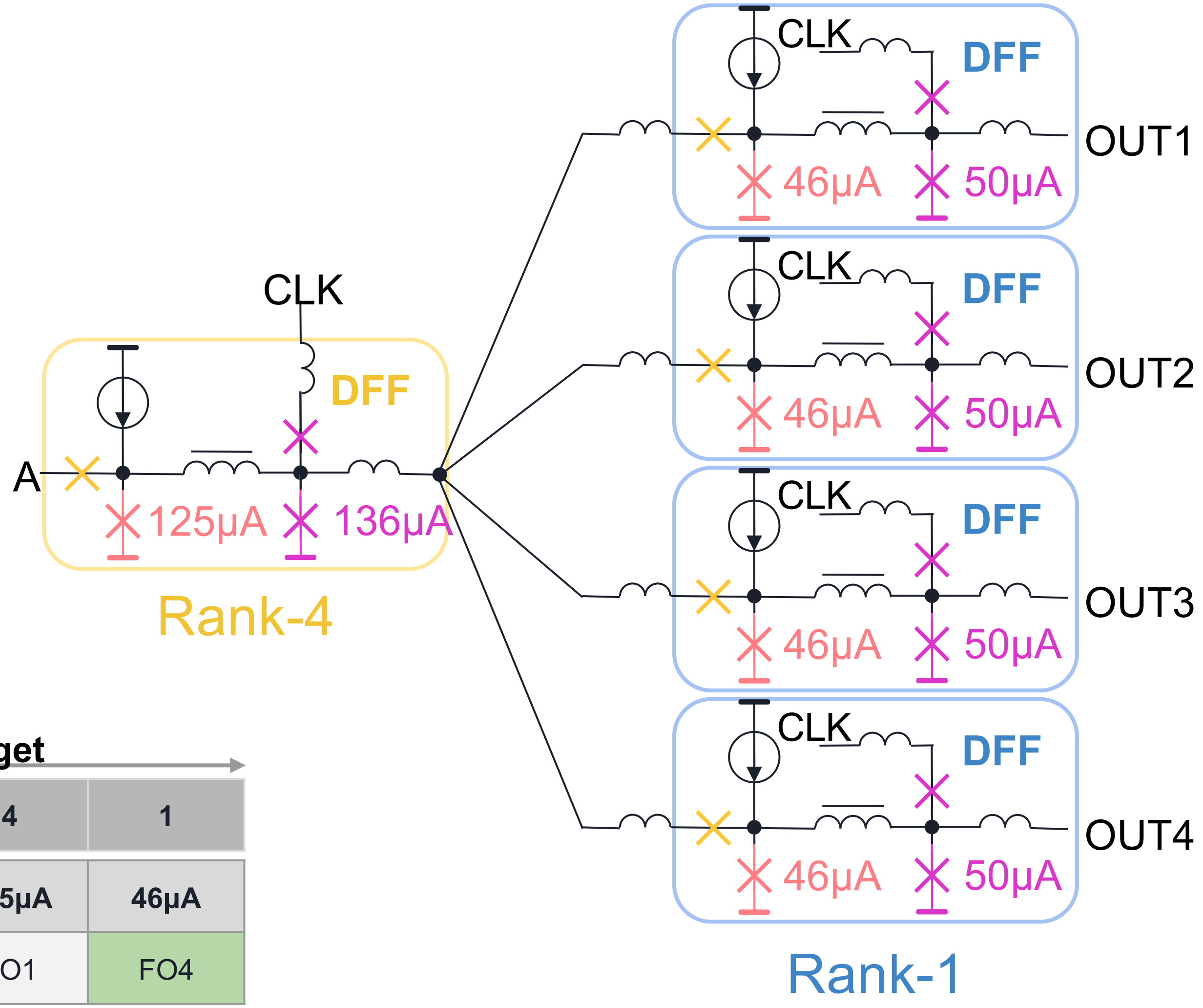
Target

Source

| | Rank | 4 | 1 |
|---|---|---|---|
| **Rank** | **$I_C$** | **125μA** | **46μA** |
| **4** | **125μA** | FO1 | FO4 |

# Design Methodology

## 3. Flexible rank



**Target**

**Source**

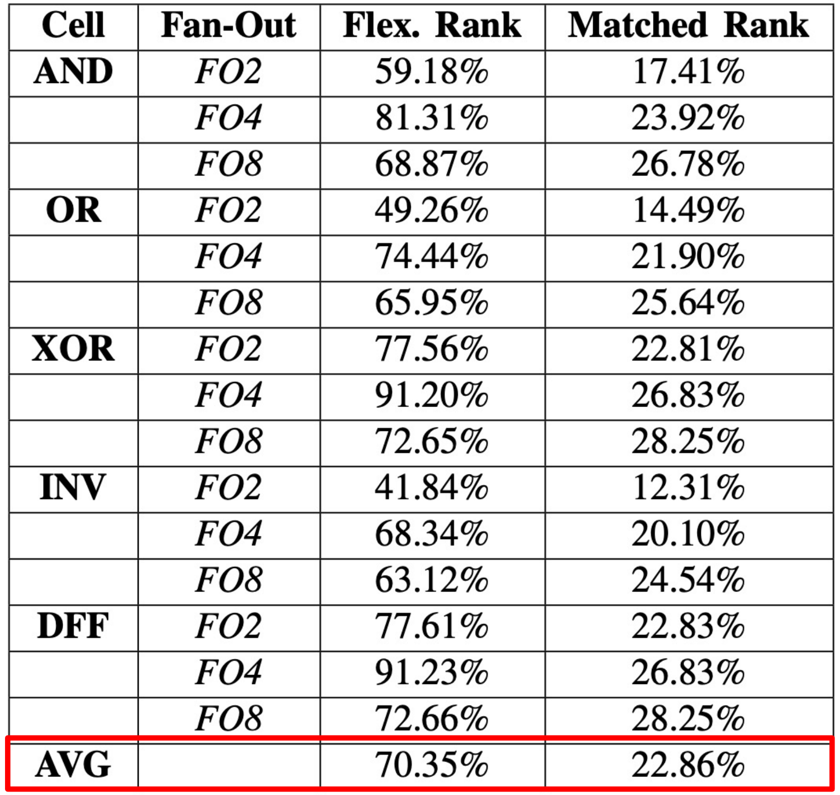
| | Rank | 4 | 1 |
|---|---|---|---|
| **Rank** | **$I_C$** | **125µA** | **46µA** |
| **4** | **125µA** | FO1 | 🟩 FO4 |

# Evaluation

## Bias margin analysis

| Configuration | Ranking | Splitters |
|---|---|---|
| JTL Chain R6:8 | +38.5 / -65.4% | - |
| JTL Chain R6:8 + FO3 | +38.5 / -57.7% | +30.8 / -53.8% |
| JTL Chain R6:8 + FO8 | +38.5 / -46.2% | +26.9 / -34.6% |
| JTL Chain R1:8 + FO8 | +42.3 / -46.2% | +26.9 / -34.6% |
| JTL Chain R6:8 + FO9 | +38.5 / -46.2% | +26.9 / -46.2% |
| Average | +39.5 / -49.1% | +28.2 / -44.9% |

## Bias current analysis



| **Cell** | **Fan-Out** | **Flex. Rank** | **Matched Rank** |
|---|---|---|---|
| **AND** | *FO2* | 59.18% | 17.41% |
| | *FO4* | 81.31% | 23.92% |
| | *FO8* | 68.87% | 26.78% |
| **OR** | *FO2* | 49.26% | 14.49% |
| | *FO4* | 74.44% | 21.90% |
| | *FO8* | 65.95% | 25.64% |
| **XOR** | *FO2* | 77.56% | 22.81% |
| | *FO4* | 91.20% | 26.83% |
| | *FO8* | 72.65% | 28.25% |
| **INV** | *FO2* | 41.84% | 12.31% |
| | *FO4* | 68.34% | 20.10% |
| | *FO8* | 63.12% | 24.54% |
| **DFF** | *FO2* | 77.61% | 22.83% |
| | *FO4* | 91.23% | 26.83% |
| | *FO8* | 72.66% | 28.25% |
| **AVG** | | 70.35% | 22.86% |

**Percent Savings**

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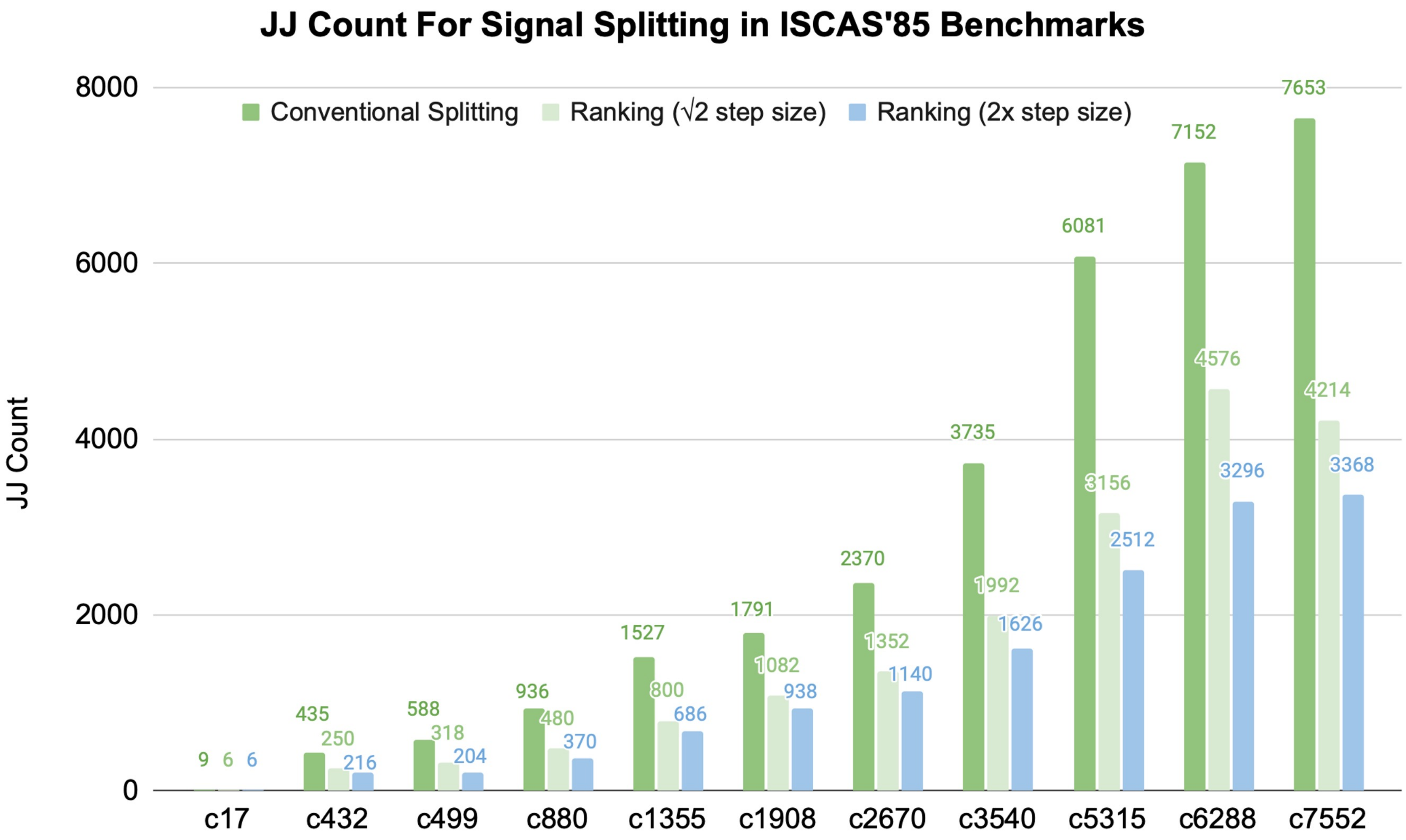
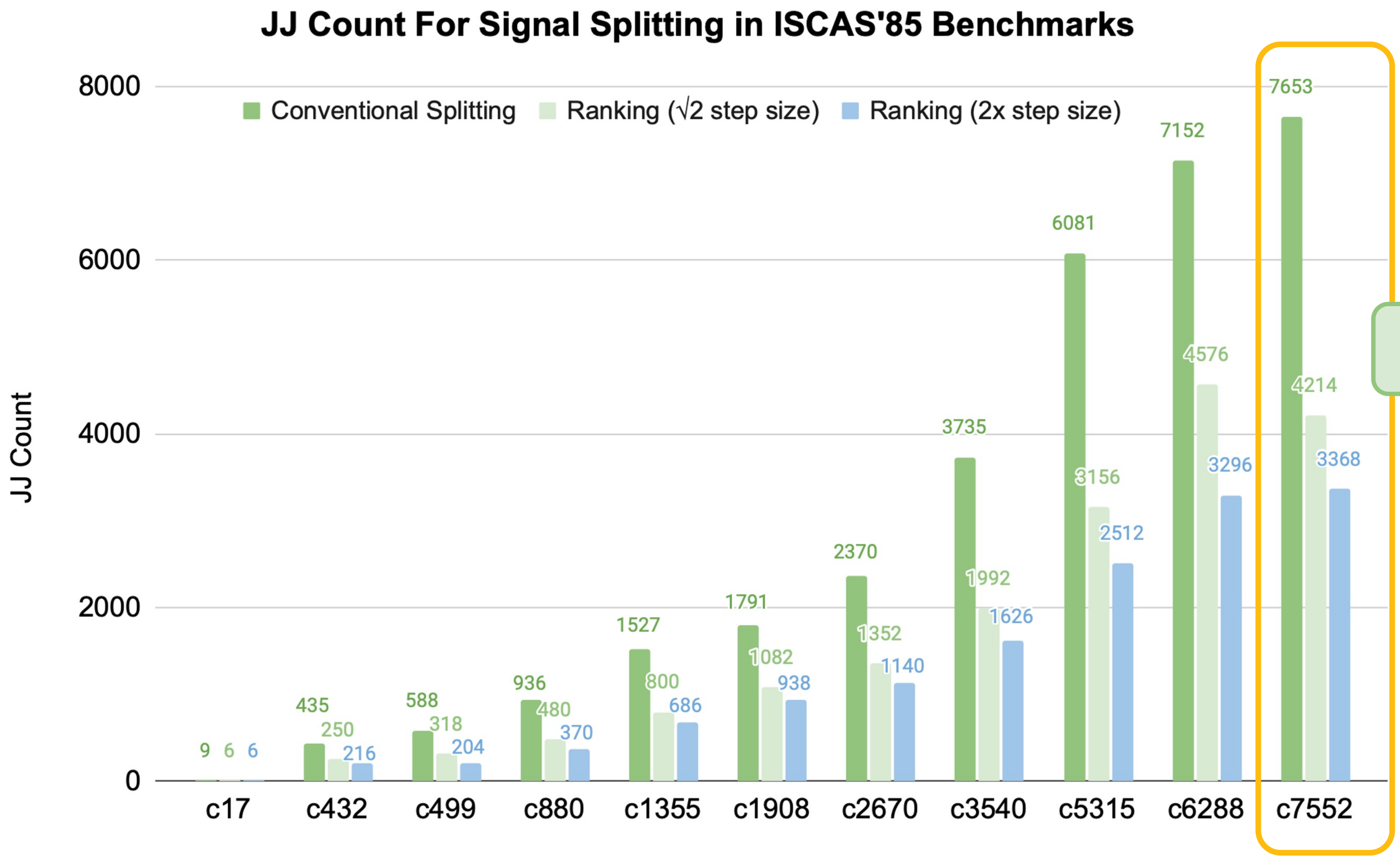
# Evaluation



JJ Count For Signal Splitting in ISCAS'85 Benchmarks

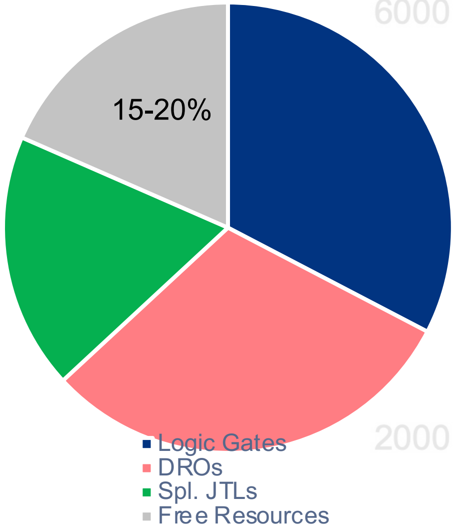
# Evaluation

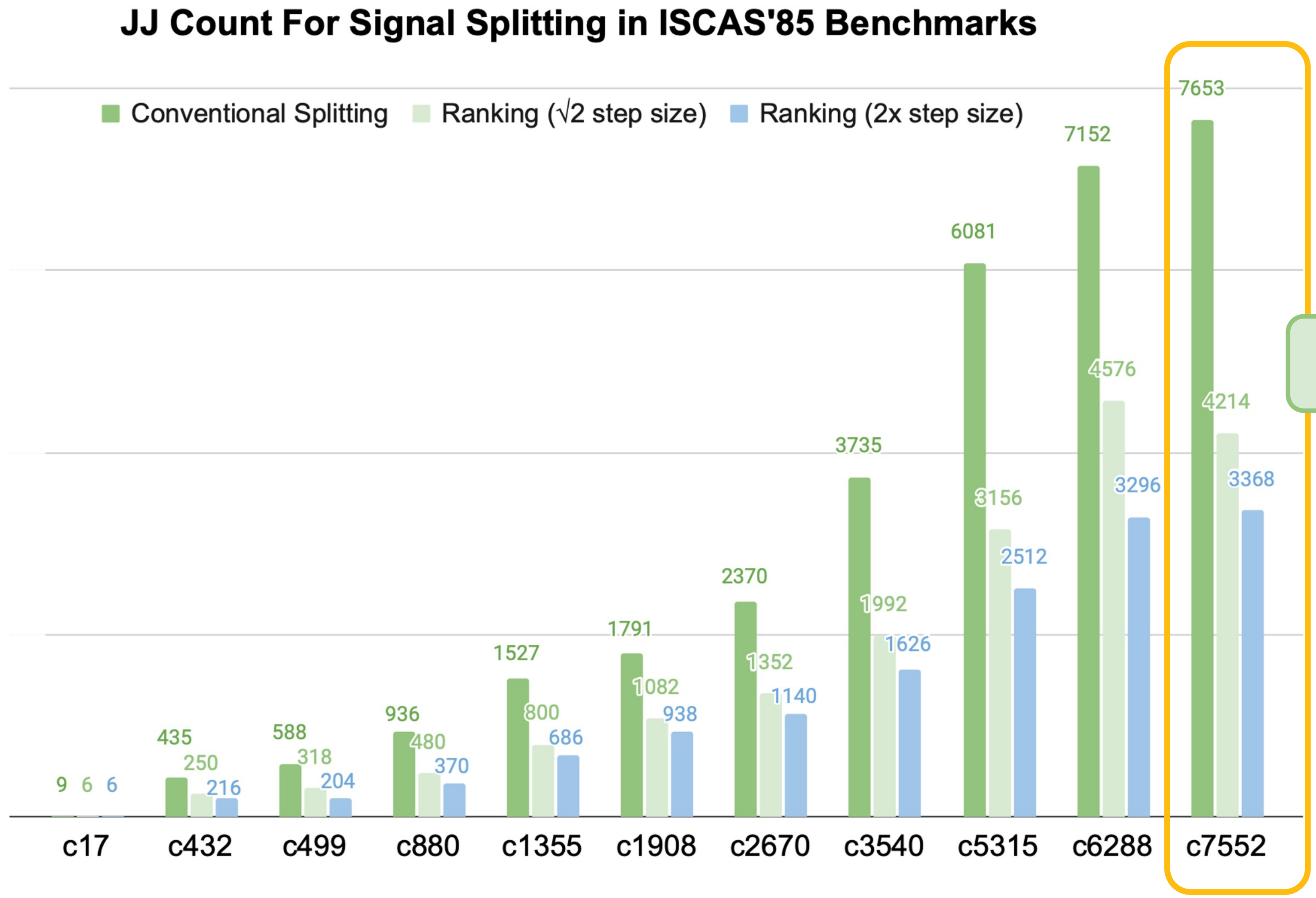


**Saves ~45%**

**Saves ~56%**

# Evaluation





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*IEEE-CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), March 2023. Presentation 1EPo2E-05 given at Applied Superconductivity Conference, Honolulu, HI, USA, October 23-28, 2022.*

# Summary

## Key contributions

- JJ borrowing
- Cell ranking

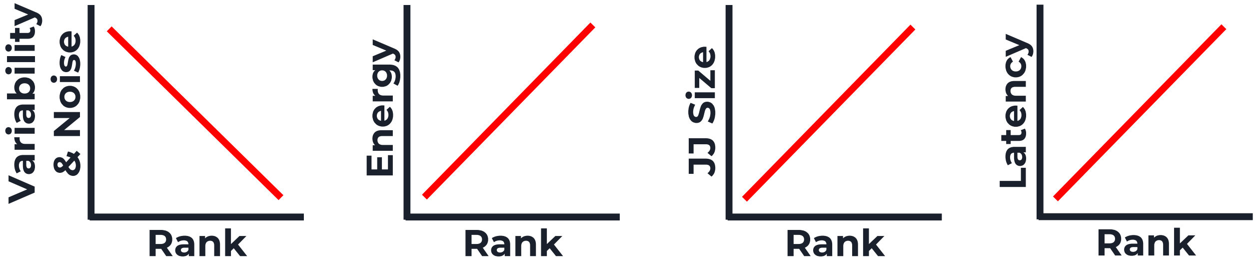
arXiv https://arxiv.org/abs/2206.07817
https://github.com/UCSBarchlab/SFQ-Ranking

## Results

- Saves up to 45% of splitting JJs/ 15% of the total JJ count
- Up to ~70% lower bias current for splitting
- No bias margin degradation

## Next task

- Integration with optimizers
- Align ranking methodology with design goals



# Questions?

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