Cut-Expansion in Proof-Nets of Multiplicative Linear Logic

Rémi Di Guardia

IRIF (CNRS, Université Paris Cité)

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Introduction

Cut-reduction

$$\dfrac{\dfrac{\overset{\pi_1}{\vdash B^\perp, A^\perp, \Gamma}}{\vdash B^\perp \parr A^\perp, \Gamma}\ (\parr) \qquad \dfrac{\overset{\pi_2}{\vdash A, \Delta} \quad \overset{\pi_3}{\vdash B, \Sigma}}{\vdash A \otimes B, \Delta, \Sigma}\ (\otimes)}{\vdash \Gamma, \Delta, \Sigma}\ (cut) \quad \longrightarrow \quad \dfrac{\dfrac{\overset{\pi_1}{\vdash B^\perp, A^\perp, \Gamma} \quad \overset{\pi_3}{\vdash B, \Sigma}}{\vdash A^\perp, \Gamma, \Sigma}\ (cut) \qquad \overset{\pi_2}{\vdash A, \Delta}}{\vdash \Gamma, \Delta, \Sigma}\ (cut)$$

Very useful

Example of result: can reduce to a cut-free proof (weak normalization)

Applications:

- No proof of falsity $\perp$ or 0
- Proof search
- ...

Introduction

Cut-expansion

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Useful?

Example of result: can expand to a proof with only one cut-rule, at its root

Applications:

- Craig's interpolation – following [Sau25][1] and [FOS25][2]
- Denotational semantic – used in [EFP24][3]

[1] Interpolation as Cut-Introduction: On the Computational Content of Craig-Lyndon Interpolation
[2] On Correctness, Sequentialization and Interpolation
[3] Bayesian Networks and Proof-Nets: a proof-theoretical account of Bayesian Inference

Introduction

Cut-expansion

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Example of result: can expand to a proof with only one cut-rule, at its root

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- Craig's interpolation – following [Sau25][1] and [FOS25][2]
- Denotational semantic – used in [EFP24][3]

This talk: Simple proof of this result in *proof-nets*, adaptable enough to be transferred in most fragments of LL

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Plan

- **Proof-Nets & Cut-Reduction**
- **Expanding to a unique *cut* & Applications**
  - Craig's Interpolation
  - Denotational Semantic
- **Proof of the Expansion to a unique *cut***
- **Extension to full Linear Logic**

Proof-nets for unit-free Multiplicative Linear Logic

- **Formula**

$A, B \ ::= \ X \mid X^{\perp} \mid A \otimes B \mid A \parr B$

- **Orthogonal**

$(X^{\perp})^{\perp} = X \quad (A \otimes B)^{\perp} = B^{\perp} \parr A^{\perp}$

$(A \parr B)^{\perp} = B^{\perp} \otimes A^{\perp}$

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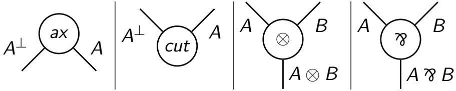
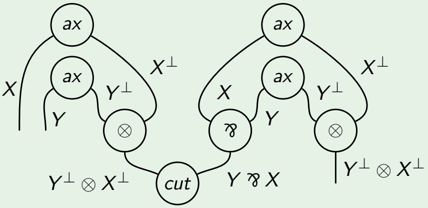
- **Proof-Structure**

Partial graph built from:



Pending edges = sequent proved



Proof of $\vdash X, Y, Y^{\perp} \otimes X^{\perp}$

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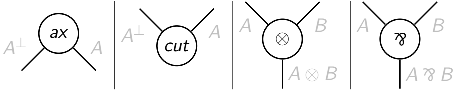

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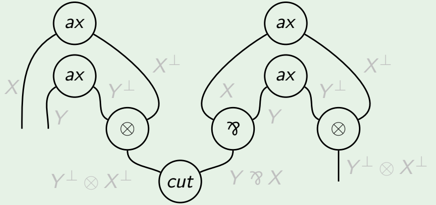

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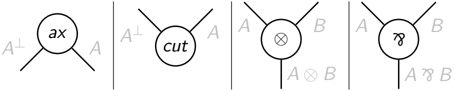

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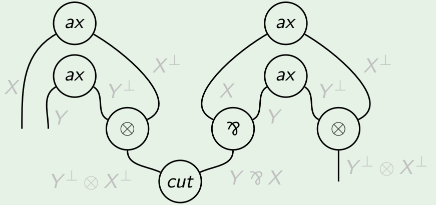
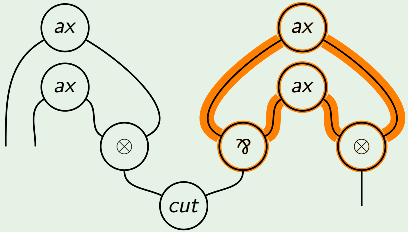


Proof of $\vdash X, Y, Y^\perp \otimes X^\perp$

- **Proof-Net**

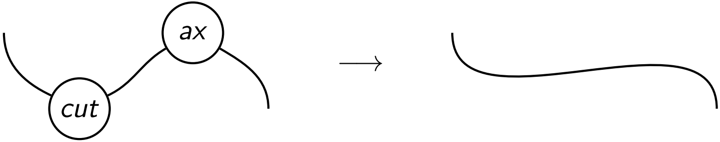
Danos-Regnier correctness criterion: each cycle contains the two edges above some $\parr$



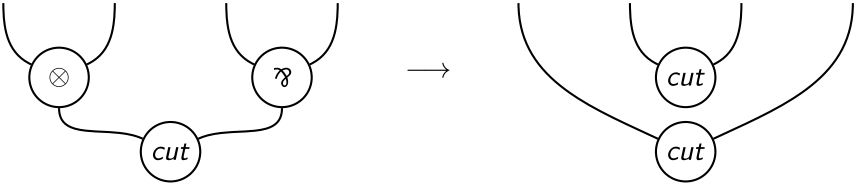
We work with *mix* to simplify, but everything also holds without it.

Cut-Reduction

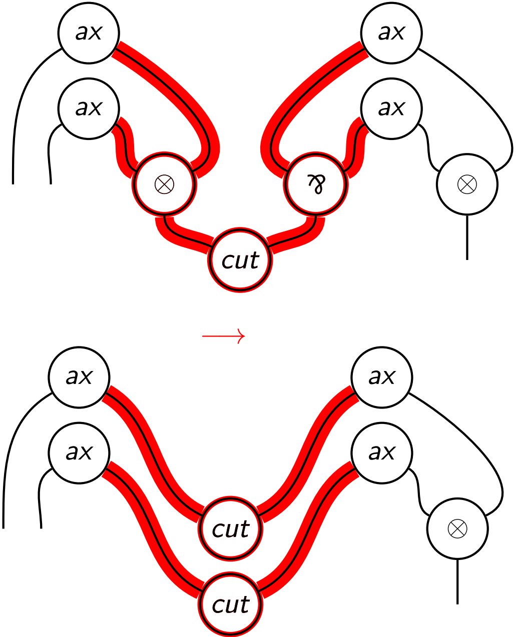
- *ax* **case**



- $⅋ - \otimes$ **case**



Cut-reduction on an example



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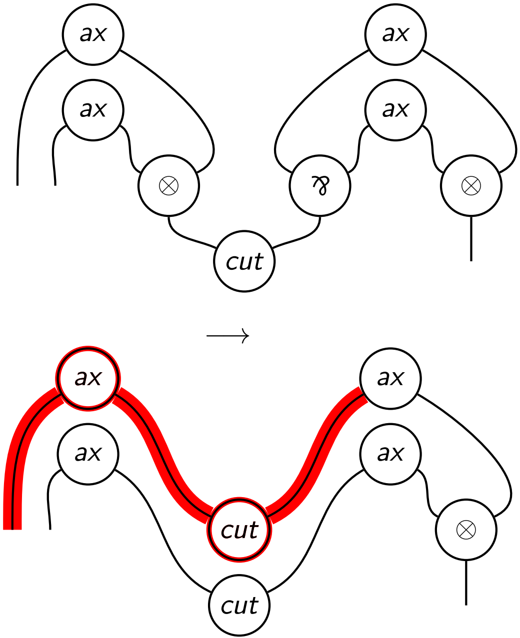

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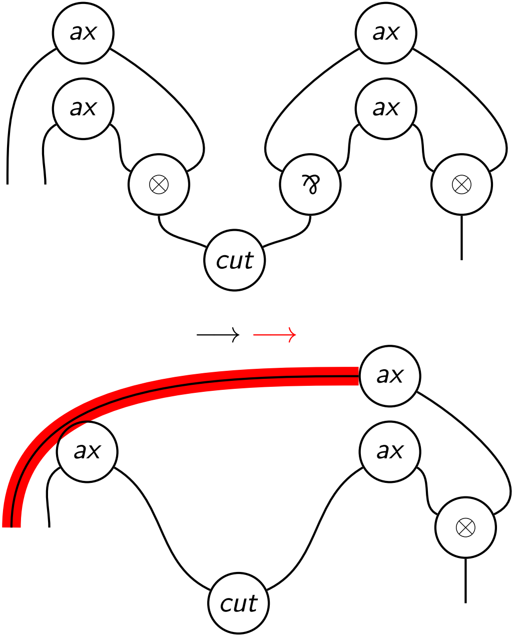

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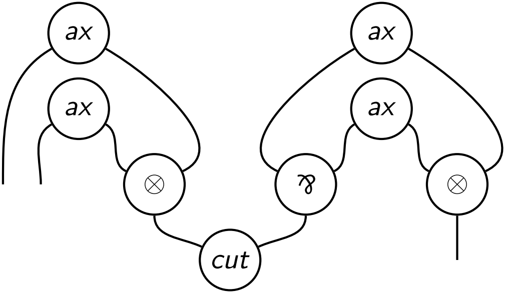
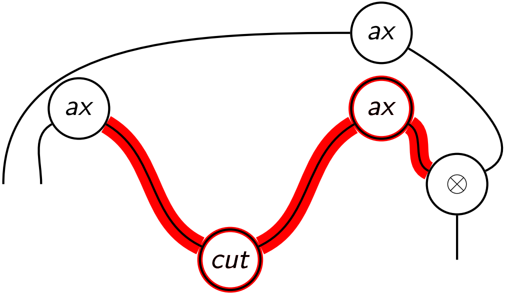


$\longrightarrow \longrightarrow$



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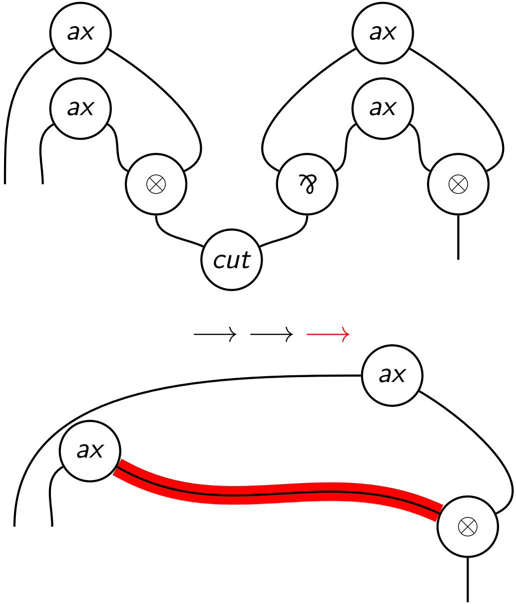


On Correctness and Cut-expansion

Has a cut? Can always reduce it.

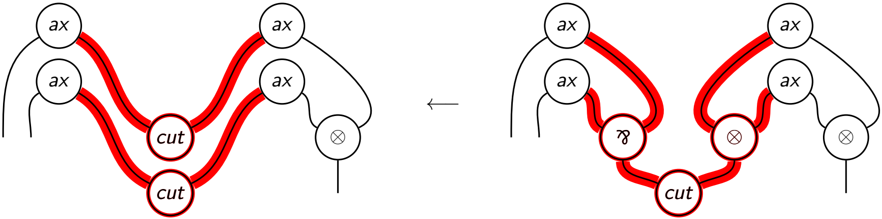
Lemma

If $\mathcal{P}$ is a proof-net and $\mathcal{P} \to \mathcal{Q}$, then $\mathcal{Q}$ is a proof-net.

Has 2 cuts? Can always expand them.

Fact

If $\mathcal{P}$ is a proof-net and $\mathcal{P} \leftarrow \mathcal{Q}$, then $\mathcal{Q}$ ***may not be*** *a proof-net.*



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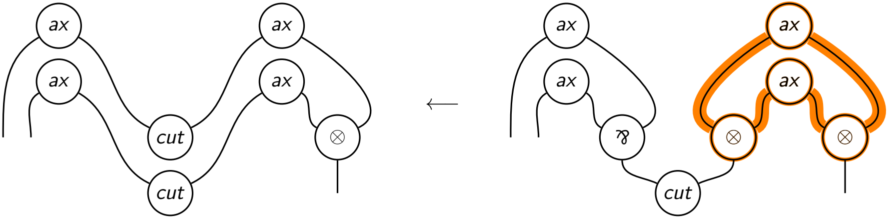

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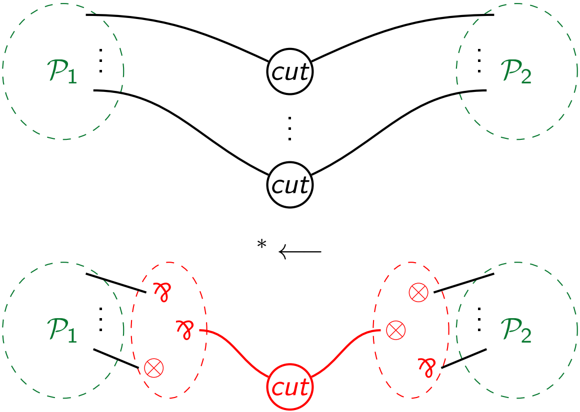
Expanding to a unique *cut*

Proposition: Expanding to a unique *cut*

Take a proof-net $\mathcal{P}$ made of two sub-graphs linked by $n \geq 1$ cut-vertices. There is a sequence of $n-1$ $\parr - \otimes$ cut-expansion steps on these vertices yielding a ***proof-net****.*

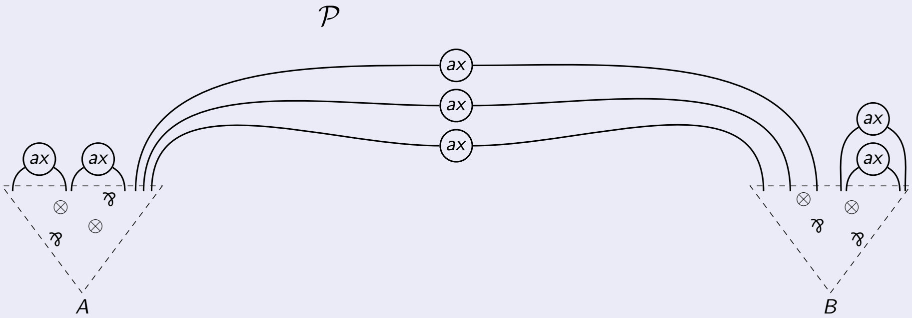


Application: Craig's Interpolation

Proof-relevant Craig's interpolation [Sau25; FOS25]

Set $\mathcal{P}$ a cut-free proof-net of $\vdash A, B$.
There is a formula C whose atoms appear in both A and B and cut-free proof-nets $\mathcal{P}_1$ of $\vdash A, C$ and $\mathcal{P}_2$ of $\vdash C^\perp, B$ such that $\mathcal{P} \overset{*}{\leftarrow} \mathcal{P}_1$ cut $\mathcal{P}_2$.

New Proof.



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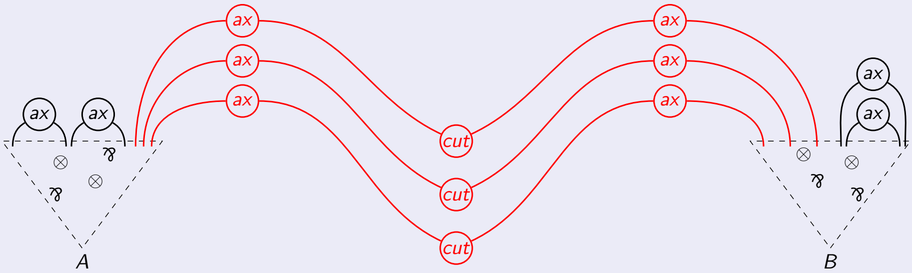
New Proof.

$\mathcal{P} \ ^* \leftarrow$



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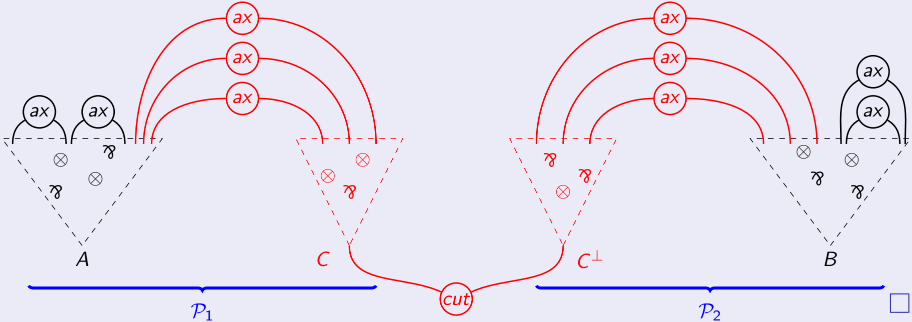
New Proof.

$$\mathcal{P} \ {}^* \!\leftarrow {}^* \!\leftarrow \mathcal{P}_1 \ \mathit{cut} \ \mathcal{P}_2$$



□

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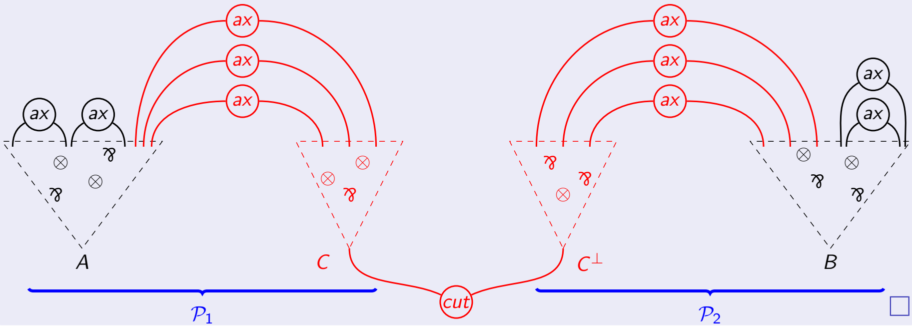
(Unless $\mathcal{P} = \mathcal{P}_1 \uplus \mathcal{P}_2$ with $\mathcal{P}_1$ of conclusion $\vdash A$ and $\mathcal{P}_2$ of conclusion $\vdash B$.)

New Proof.

$$\mathcal{P} \overset{*}{\leftarrow} \overset{*}{\leftarrow} \mathcal{P}_1 \textit{ cut } \mathcal{P}_2$$



□

Differences with [FOS25]

Proof-relevant Craig's interpolation [Sau25; FOS25]

Set $\mathcal{P}$ a connected cut-free proof-net of $\vdash A, B$.
There is a formula C whose atoms appear in both A and B and cut-free proof-nets $\mathcal{P}_1$ of $\vdash A, C$ and $\mathcal{P}_2$ of $\vdash C^\perp, B$ such that $\mathcal{P} \; ^* \leftarrow \mathcal{P}_1$ cut $\mathcal{P}_2$.

No mix-rule $\Longrightarrow$ connected proof-net.

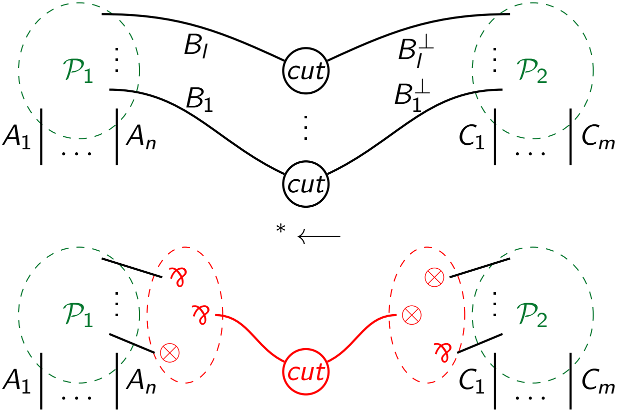
[FOS25] also proves Craig's interpolation in proof-nets but:

- it needs the units $\perp$ and 1, even if $\mathcal{P}$ has none;
- it proceeds by **parsing** (*i.e.* goes top-down) so cannot have mix; meanwhile, we will proceed by **splitting vertices** (*i.e.* bottom-up).

Application: Denotational Semantic

Useful for **compositionality** (*e.g.* in [EFP24]): given *interpretations* $[\![\mathcal{P}_1]\!]$ and $[\![\mathcal{P}_2]\!]$, how to get the *interpretation* of the full net?

$\rightsquigarrow$ Easy when **only one** *cut*, otherwise *typing* problem: given $[\![\mathcal{P}_1]\!] : \bigotimes A_i \to \bigparr B_j$ and $[\![\mathcal{P}_2]\!] : \bigotimes B_j \to \bigparr C_k$, want $\bigotimes A_i \to \bigparr C_k$



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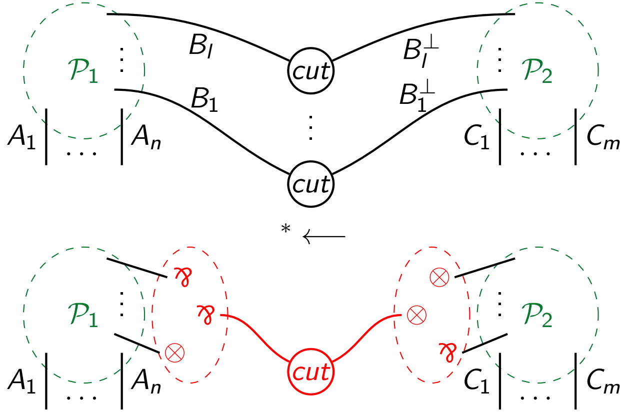

[EFP24]'solution with the *same result* as here, but using **parsing** again!

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Reasoning

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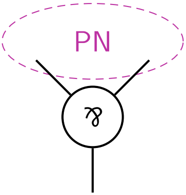
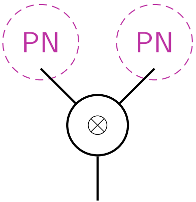
*Take a proof-net $\mathcal{P}$ made of two sub-graphs linked by $n \geq 1$ cut-vertices. There is a sequence of $n - 1$ ⅋ $- \otimes$ cut-expansion steps on these vertices yielding a **proof-net**.*

- Proof by induction on $\#|\text{vertices}|$
- Main consideration: when adding a $\otimes$, we ensure it creates no “bad cycle”
- Case study using a proof-net with a *cut* always has a **splitting vertex**:

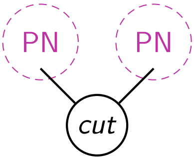
- ⅋-vertex



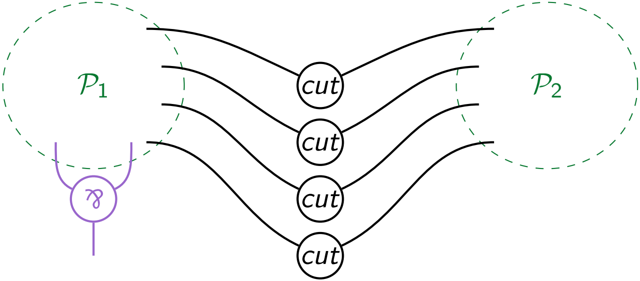
- $\otimes$-vertex



- *cut*-vertex



Splitting ⅋



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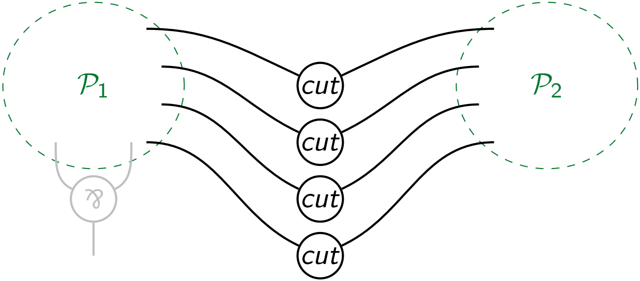
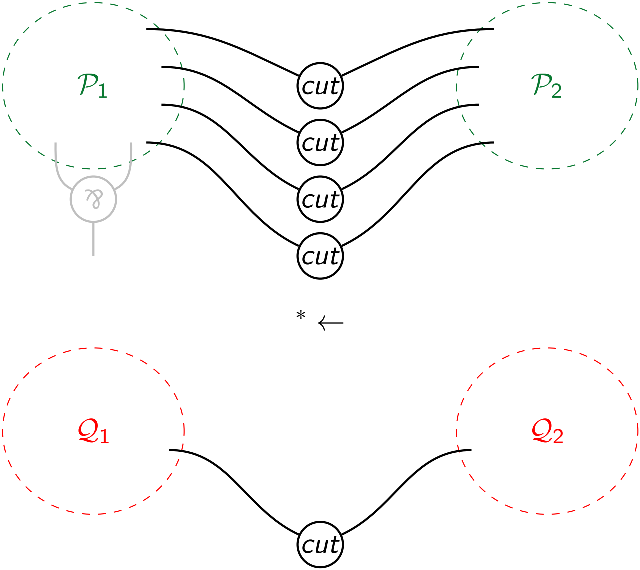
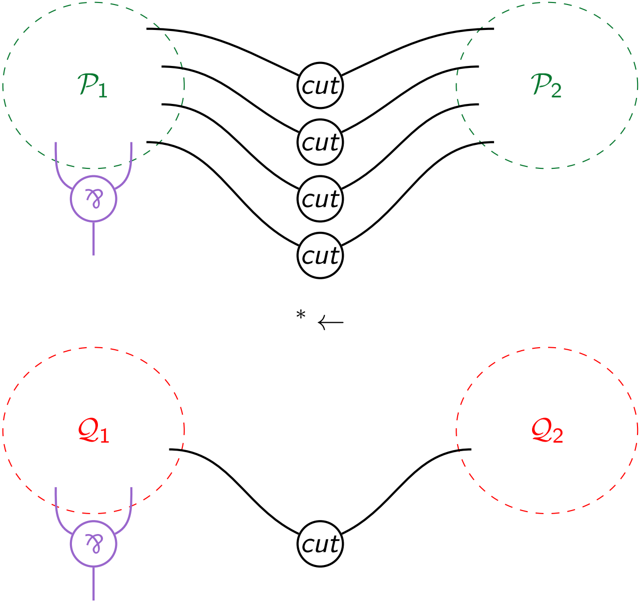


Splitting ⅋



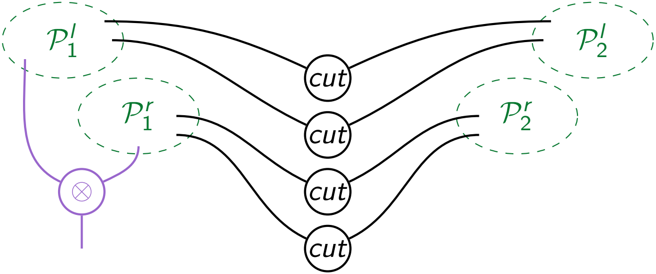
$\mathcal{P}_1$
⅋
cut
cut
cut
cut
$\mathcal{P}_2$
$* \leftarrow$
$\mathcal{Q}_1$
cut
$\mathcal{Q}_2$

Splitting ⅋

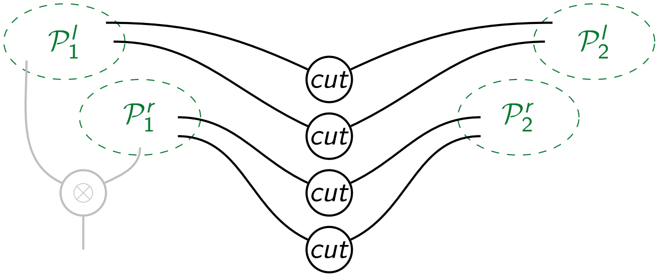


$\mathcal{P}_1$
$\mathcal{P}_2$
cut
cut
cut
cut
⅋
$* \leftarrow$
$\mathcal{Q}_1$
$\mathcal{Q}_2$
cut
⅋

Splitting $\otimes$

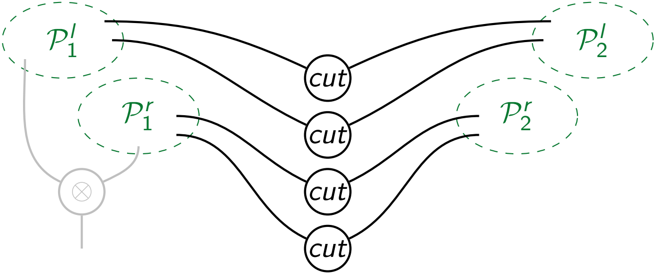


Splitting ⊗

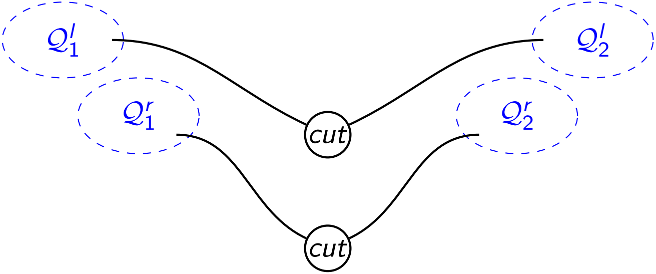


$\mathcal{P}_1^l$
$\mathcal{P}_1^r$
$\mathcal{P}_2^l$
$\mathcal{P}_2^r$
cut
cut
cut
cut
⊗

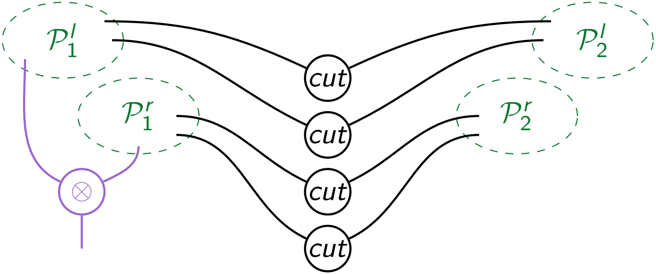
Splitting $\otimes$



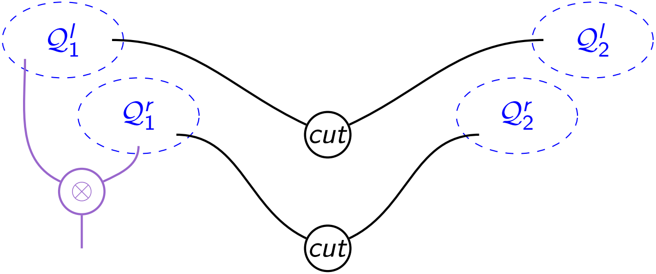
$* \leftarrow * \leftarrow$



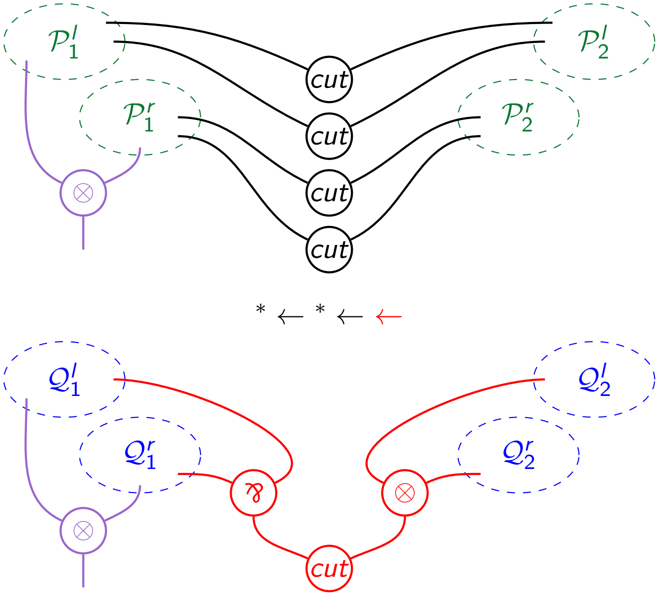
Splitting $\otimes$



$* \leftarrow * \leftarrow$

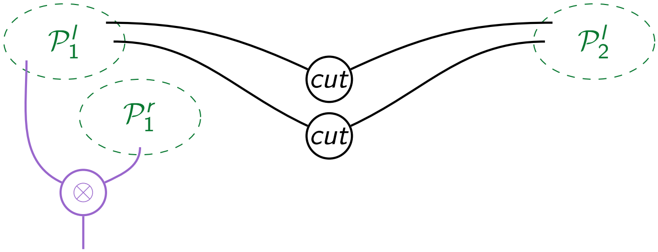


Splitting ⊗

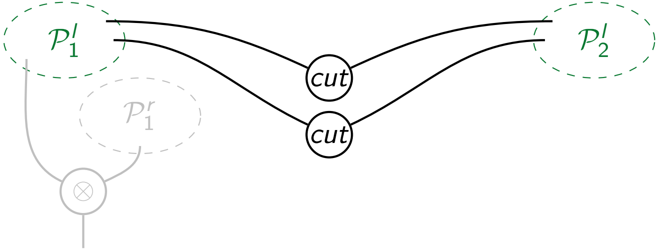


$\mathcal{P}_1^l$
$\mathcal{P}_2^l$
$\mathcal{P}_1^r$
$\mathcal{P}_2^r$
cut
cut
cut
cut
$* \leftarrow * \leftarrow \leftarrow$
$\mathcal{Q}_1^l$
$\mathcal{Q}_2^l$
$\mathcal{Q}_1^r$
$\mathcal{Q}_2^r$
cut

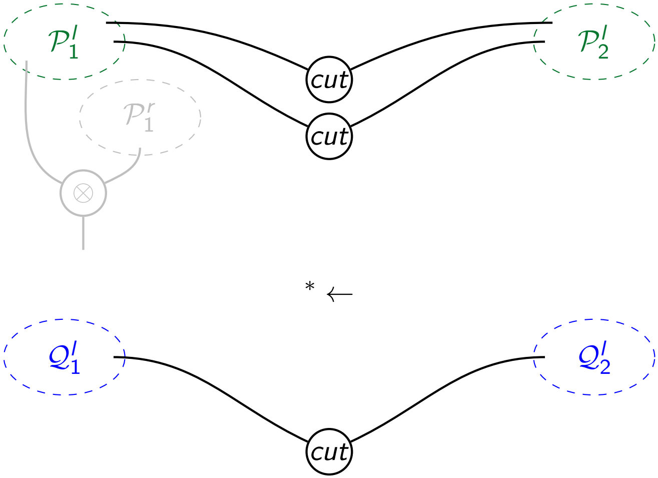
Splitting $\otimes$ *bis*



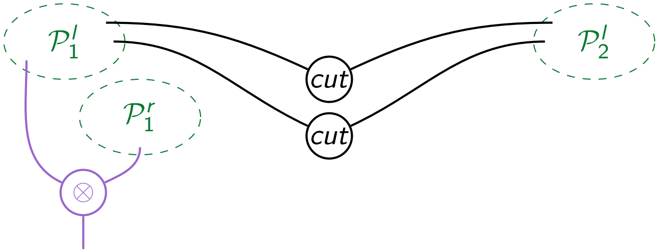
Splitting $\otimes$ *bis*



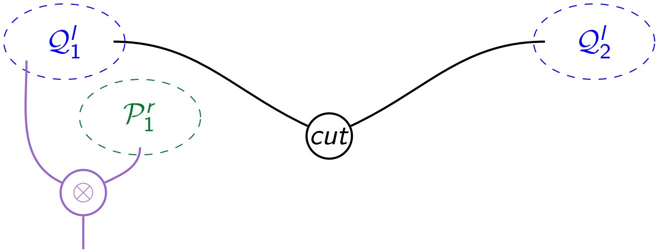
Splitting $\otimes$ *bis*



Splitting $\otimes$ *bis*

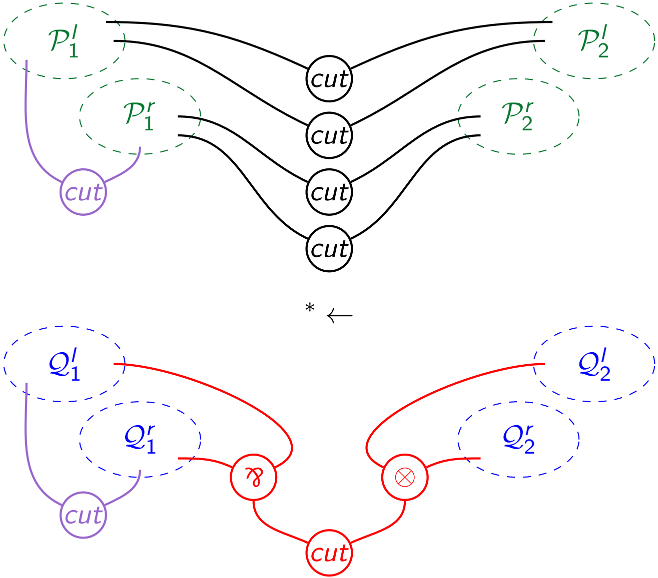


$* \leftarrow$

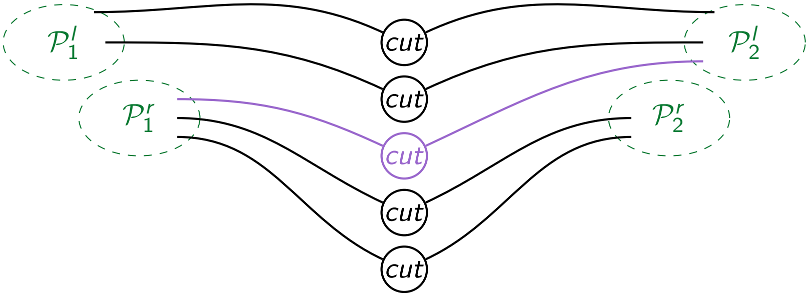


Splitting *cut*

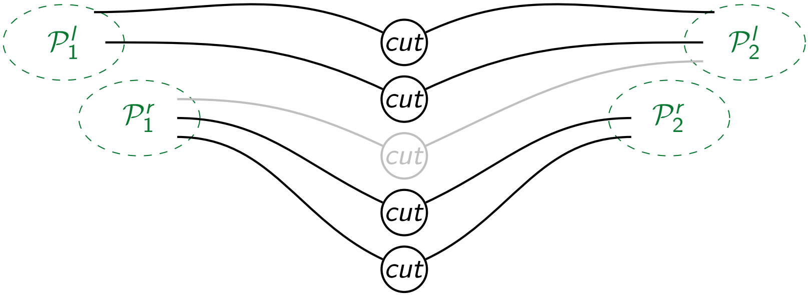
If this *cut* is not between the two sub-graphs: same as the ⊗ case.



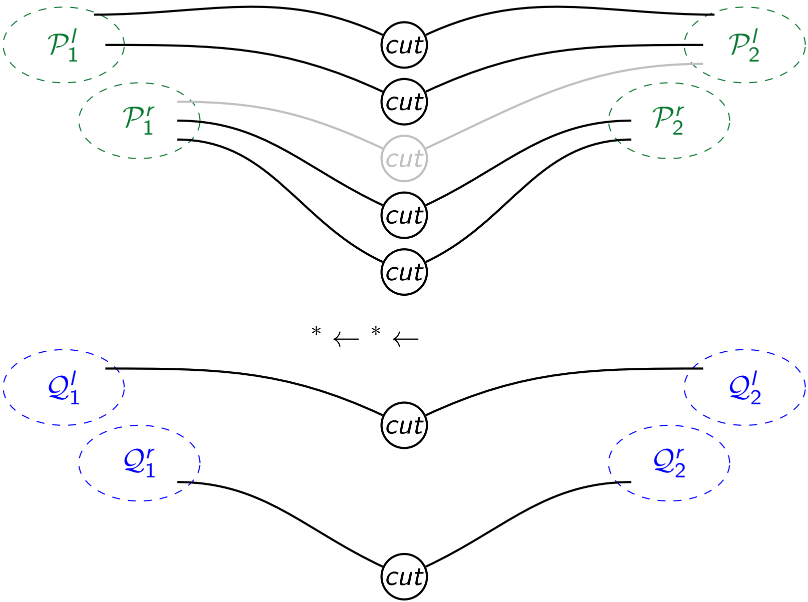
Splitting *cut*



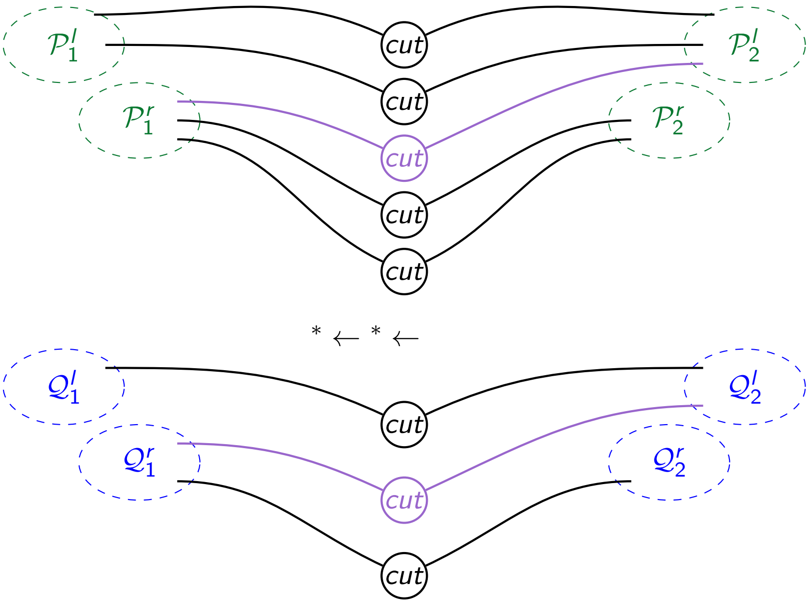
Splitting *cut*



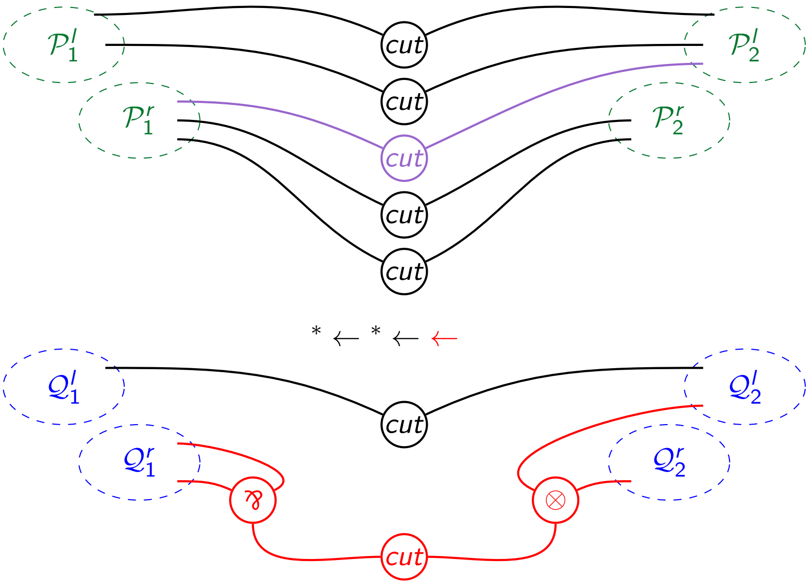
Splitting *cut*



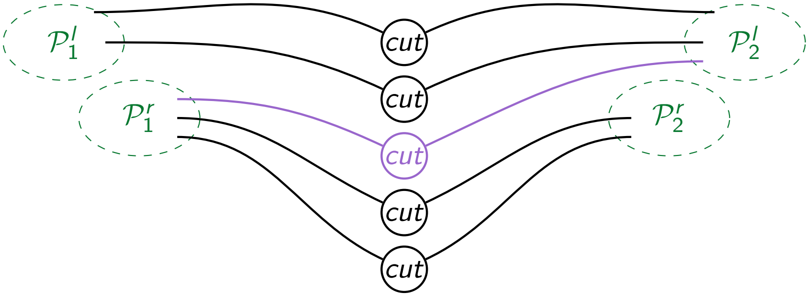
Splitting *cut*



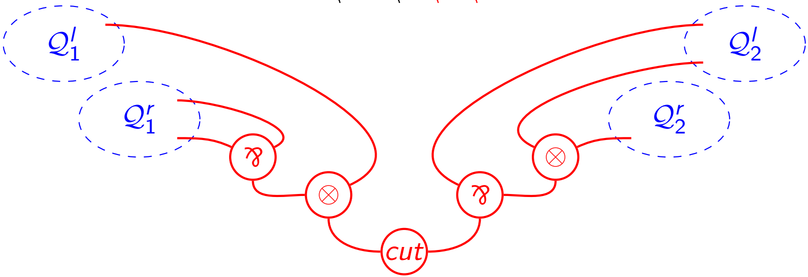
Splitting *cut*



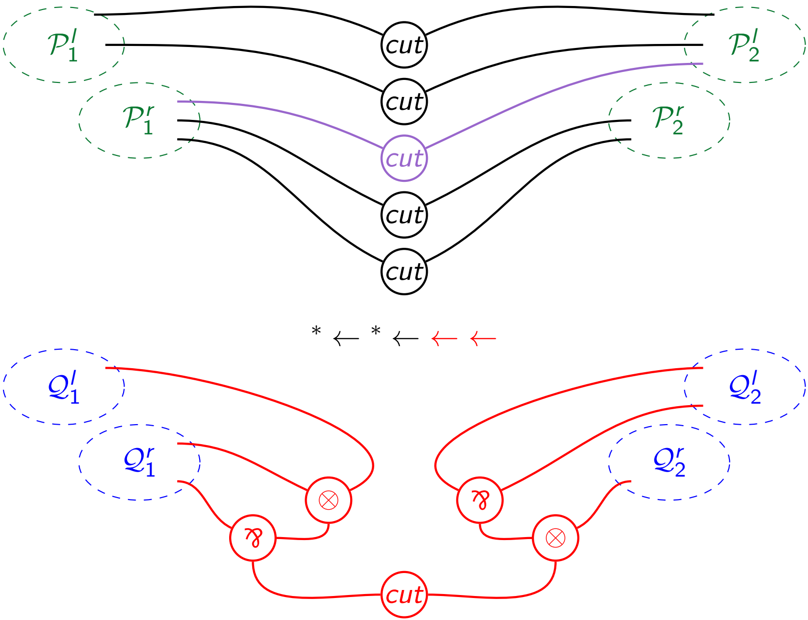
Splitting *cut*



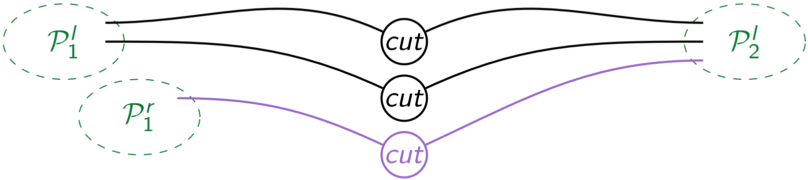
$* \leftarrow * \leftarrow \leftarrow \leftarrow$



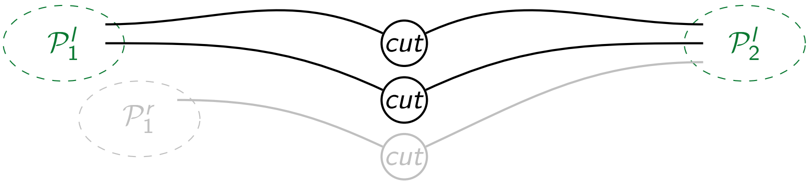
Splitting *cut*



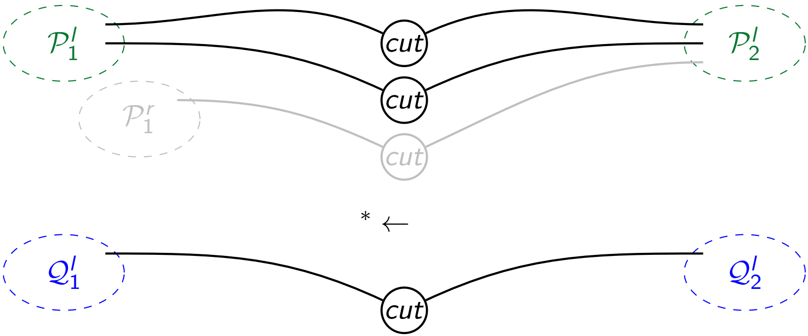
Splitting *cut* ***bis***



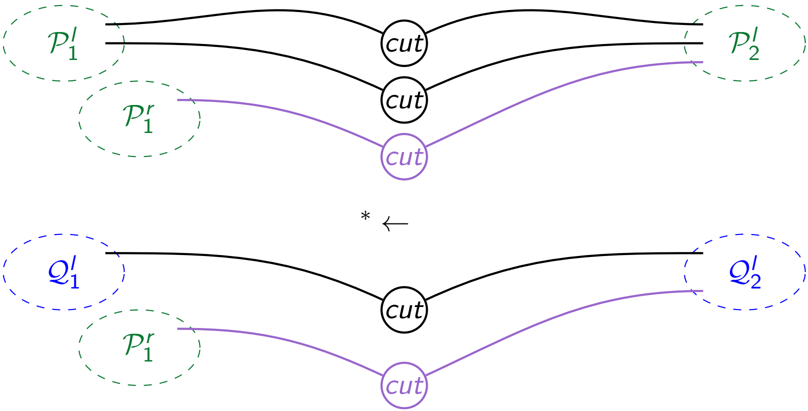
Splitting *cut* ***bis***



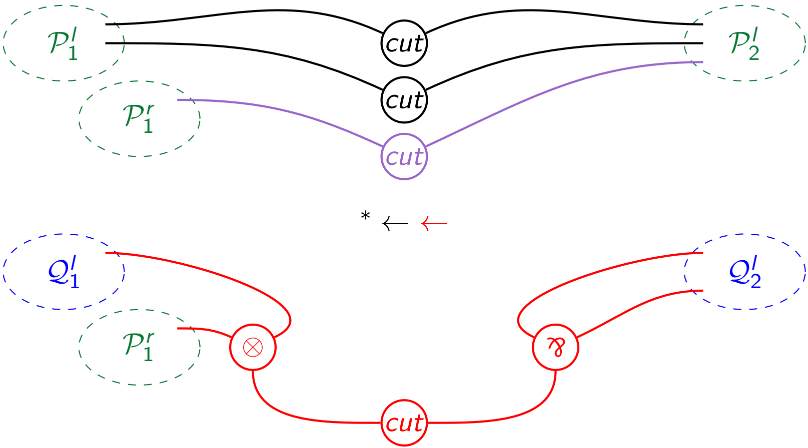
Splitting *cut* ***bis***



Splitting *cut* ***bis***



Splitting *cut* ***bis***



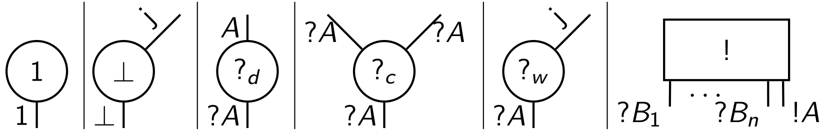
Plan

- Proof-Nets & Cut-Reduction
- Expanding to a unique *cut* & Applications
  - Craig's Interpolation
  - Denotational Semantic
- Proof of the Expansion to a unique *cut*
- **Extension to full Linear Logic**

In Proof-Nets for MLL with units & MELL

Same as for unit-free MLL!

- Proof-nets with jumps for $\perp$ and $?_w$ (or the mix-rules) and boxes for !:



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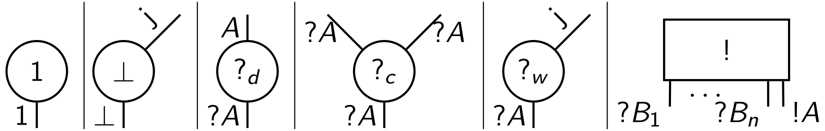


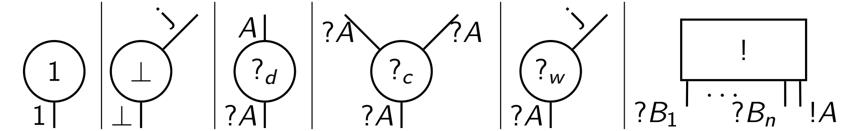
- Proof of the expansion to a unique *cut*

  Same as before: $\perp$, $?_d$, $?_c$, $?_w$ treated as a $⅋$, 1 and ! irrelevant (like *ax*)

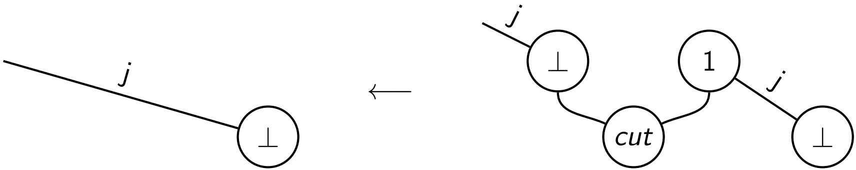
In Proof-Nets for MLL with units & MELL

Same as for unit-free MLL!

- Proof-nets with jumps for $\bot$ and $?_w$ (or the mix-rules) and boxes for !:



- Proof of the expansion to a unique *cut*
  Same as before: $\bot$, $?_d$, $?_c$, $?_w$ treated as a ⅋, 1 and ! irrelevant (like *ax*)
- Craig's interpolation just needs additional "pre-processing" steps:
  - for a *jump* between A and B:



  - for a !-*box* using both A and B: a little bit more complex, uses an *induction* (on the net associated to the promotion), then move this *cut* out of the box (by a $?_d - !$ step followed by a $! - !$ step)

In Sequent Calculus for full LL: what are cut-nets?

No proof-net for full LL $\longrightarrow$ go to sequent calculus

Definition: Derivation corresponding to a cut-net

A proof derivation π of $\vdash \Gamma$ is a **cut-derivation** if, denoting (A_i) the cut-formulas of π, there is a bipartition $\{B_1, B_2\}$ of $\Gamma \cup (\bigcup_i A_i)$ such that:

- all *ax*-rules are applied either only on sub-formulas of B_1 or only on sub-formulas of B_2; and similarly for !- and $\top$-rules;
  $\rightsquigarrow$ no *ax*, !-box or $\top$ using both sides
- given a $\bot$-rule associated to B_i, the rule just above is not a *cut*-rule and has for principal formula a sub-formula of B_i or is an $ax/!/\top$-rule between sub-formulas of B_i; and similarly for a $?_w$-rule;
  $\rightsquigarrow$ no $\bot$- or $?_w$-jump going from one side to the other
- given an $\exists$-rule associated to B_i, its witness has no atoms introduced by a $\forall$-rule associated to B_{1-i}.
  $\rightsquigarrow$ no $\forall$-jump going from one side to the other

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  $\rightsquigarrow$ no $\forall$-jump going from one side to the other

Deduce Kraig's interpolation as before: introduce a cut when one of the hypothesis of a *cut-derivation* is not respected.

In Sequent Calculus for full LL: proof

Proposition: Expanding to a unique *cut*

Take a cut-derivation π. There is a sequence of cut-expansion steps yielding a proof with only one cut-rule, at its root.

Similar proof as previously: *case study on a last rule*

⚠ & case: $\vdash A \,\&\, B, \Gamma_1, \Gamma_2$ where $\Gamma_2 = \emptyset$ and only one branch has a cut:

$$\dfrac{\dfrac{\vdash A, \Gamma_1, C_1 \qquad \vdash C_1^\perp}{\vdash A, \Gamma_1}\,(cut) \qquad \vdash B, \Gamma_1}{\vdash A \,\&\, B, \Gamma_1}\,(\&)$$

How to move the *cut* at the root?

In Sequent Calculus for full LL: proof

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How to move the *cut* at the root?

- Introduce a *cut* on $\perp - 1$ in the right branch: *no more stable by fragment*; or
- Eliminate the *cut* in the left branch: *no more only cut-expansion*.

$\rightsquigarrow$ The additive connectives need the multiplicative units to work well, but the multiplicative connectives do not! (Quantifiers also need them.)

Conclusion

- Simple visual proof of expansion to a unique *cut*, with and without mix
- Yields a proof of Craig's interpolation for unit-free MLL, MLL and MELL
- Useful for denotational semantic when typing an interface
- Adaptable in sequent calculus for full linear logic, but definitions less visual and some problems with & and quantifiers

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Thank you!

References I

[EFP24] Thomas Ehrhard, Claudia Faggian, and Michele Pagani. *Bayesian Networks and Proof-Nets: a proof-theoretical account of Bayesian Inference*. 2024. DOI: 10.48550/ARXIV.2412.20540. URL: https://arxiv.org/abs/2305.18945.

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