Logic and Probability

The Computational Connection

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Deduction at Scale Seminar, March, 2011

Inference

- **Probabilistic Graphical Models:**
  Marginal and conditional probabilities
  Most likely instantiations…

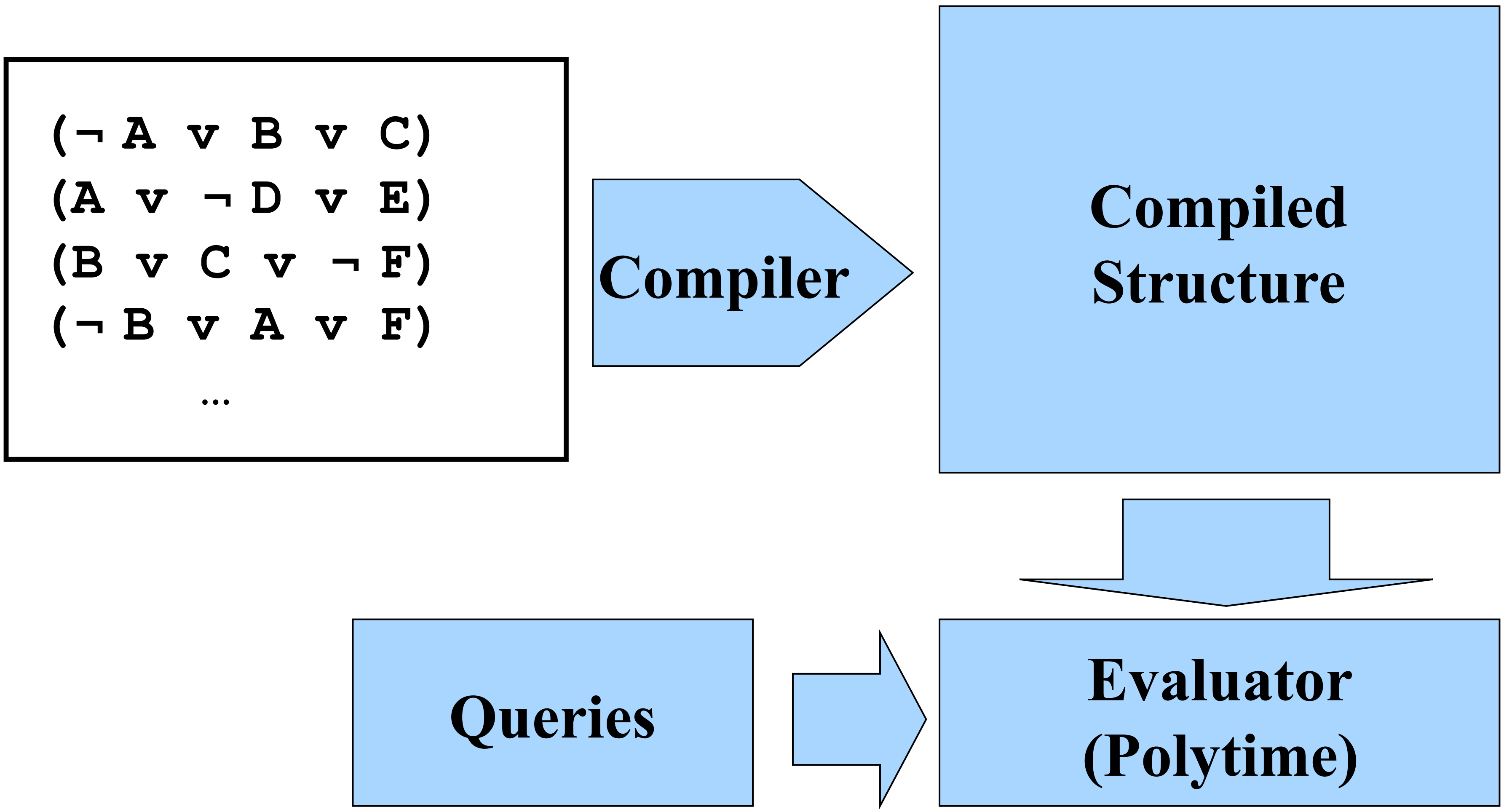
- **Propositional Knowledge Bases:**
  Logical entailment
  Existential quantification
  Model counting…

Two Main Themes

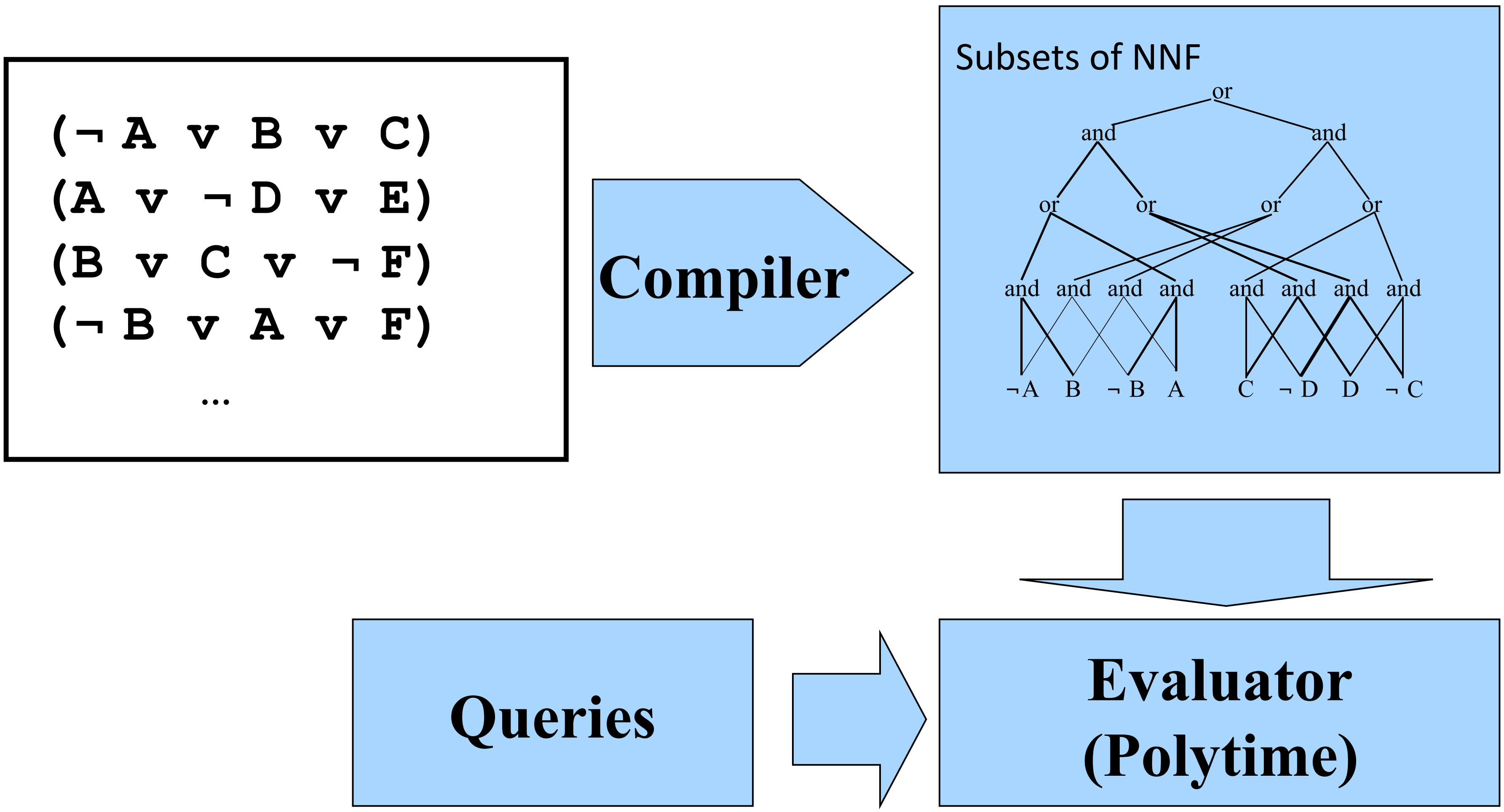
- **Exact inference as:**
  Enforcing decomposability and determinism on propositional knowledge bases

- **Approximate inference as:**
  Relaxing, compensating for, and recovering equivalence constraints (equalities)

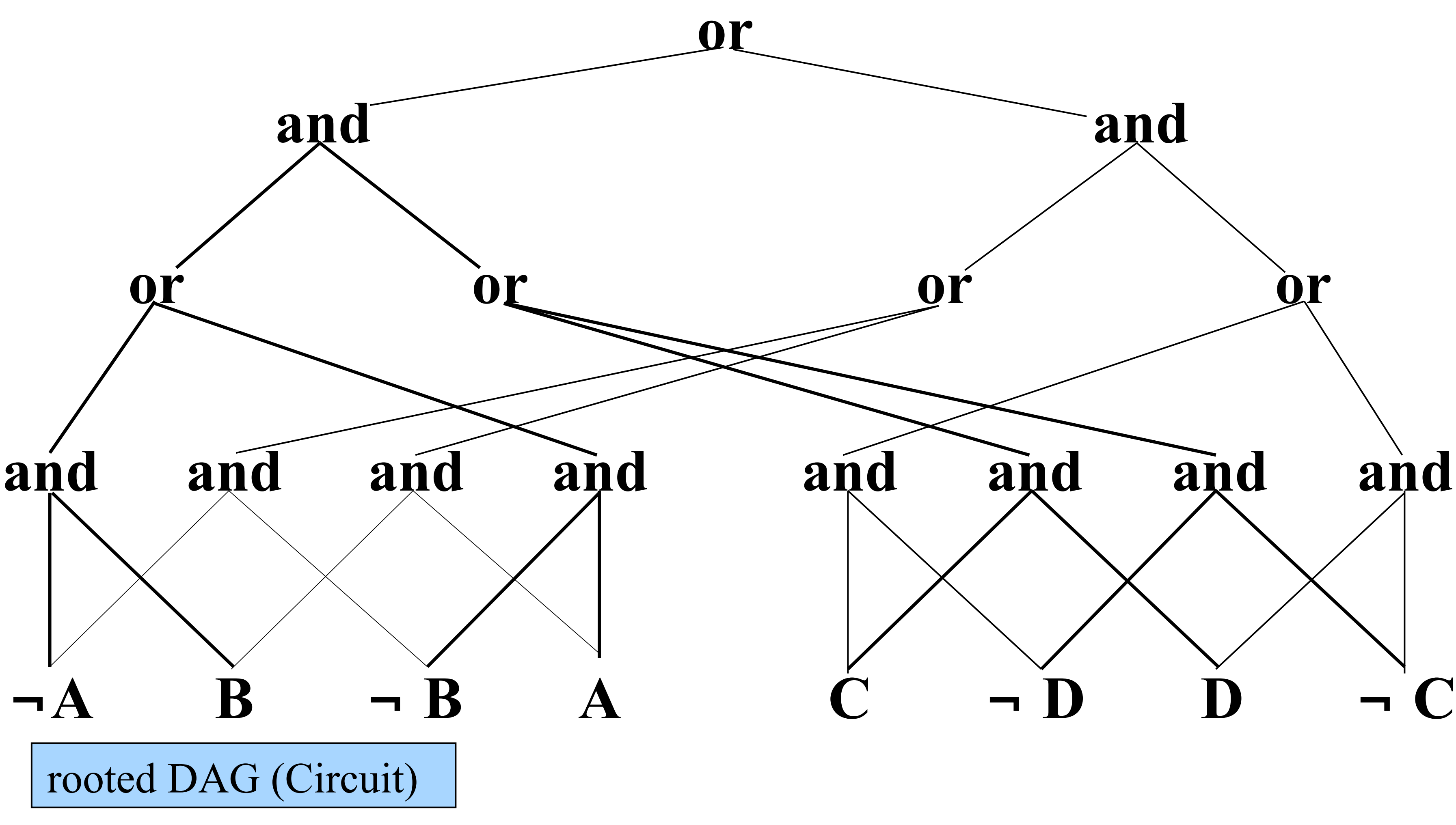
Knowledge Compilation



Knowledge Compilation

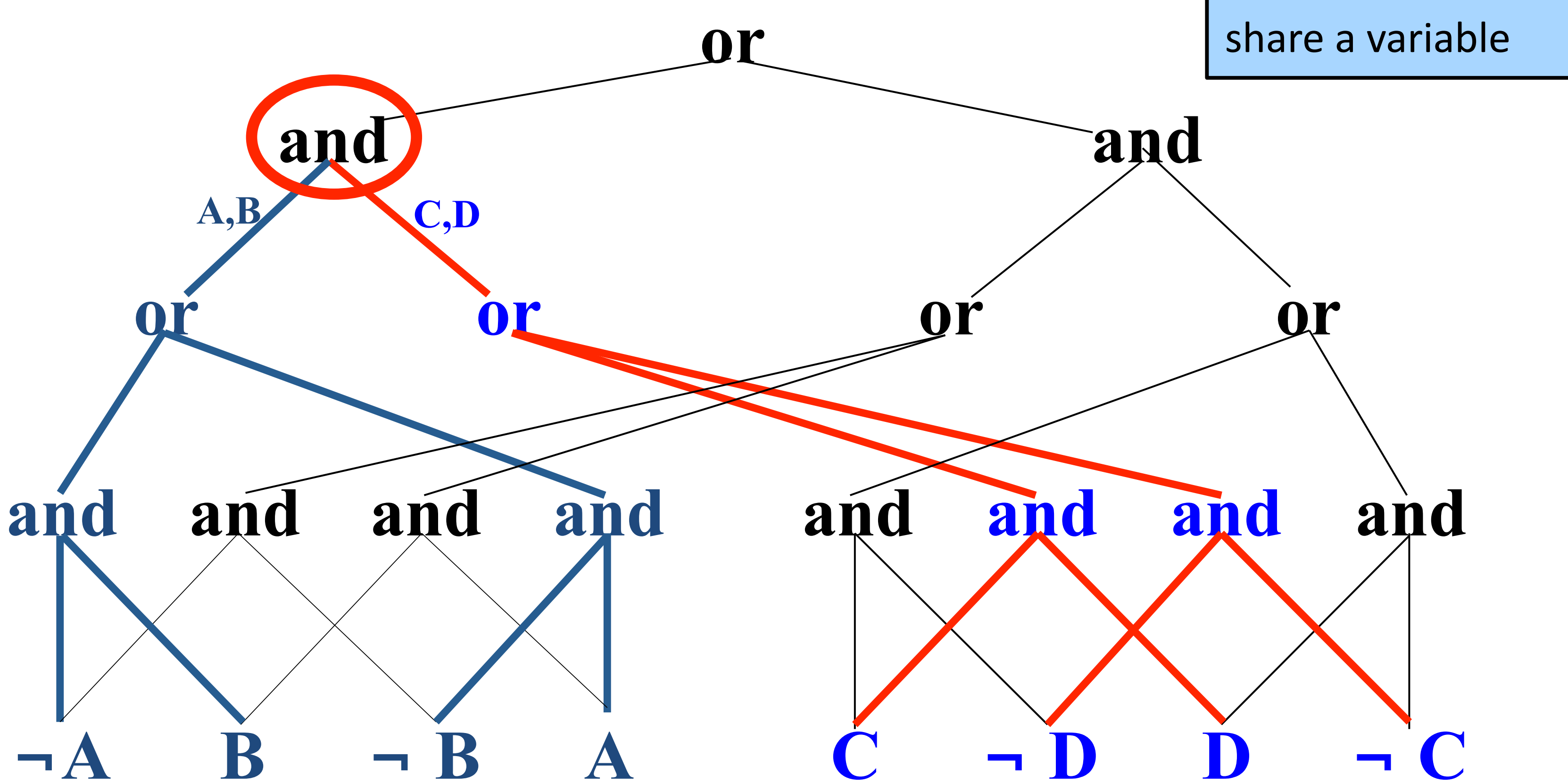


Negation Normal Form



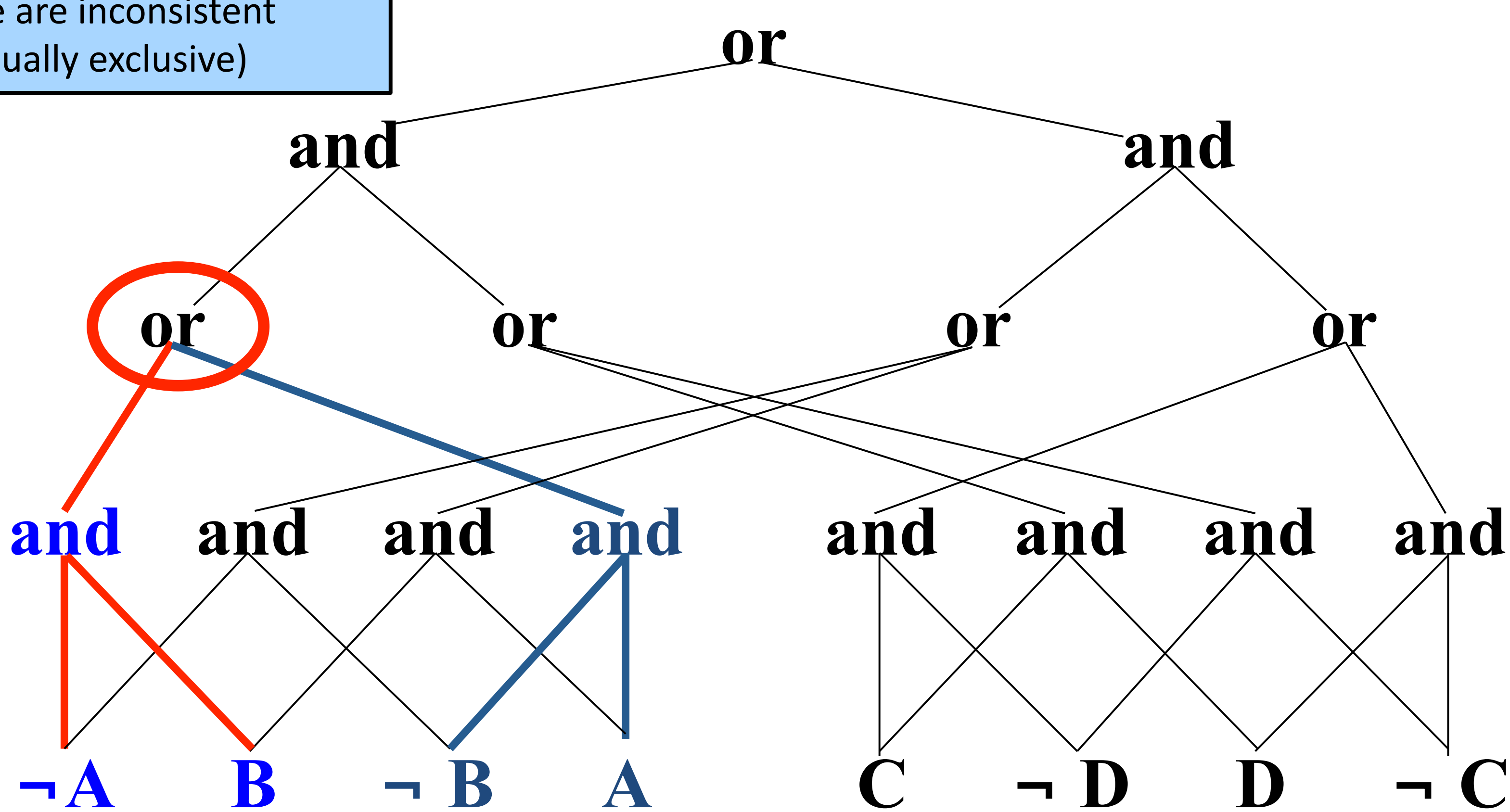
Decomposability (DNNF)

No two children of AND share a variable

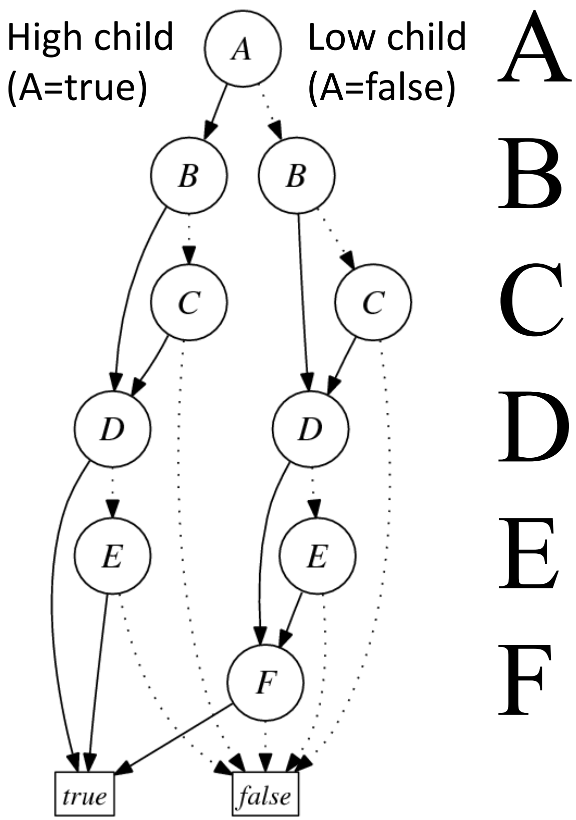


Determinism (d-DNNF)

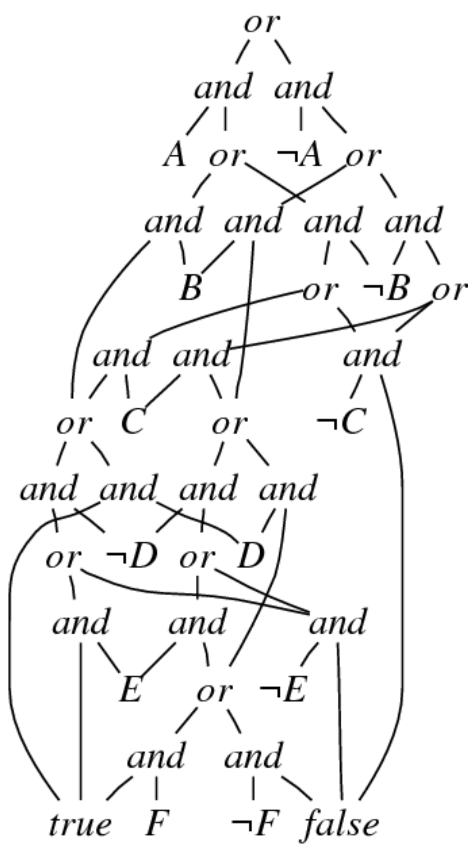
Every pair of children of or-node are inconsistent (mutually exclusive)



OBDD:
d-DNNF + Additional Properties



OBDD (traditional form)

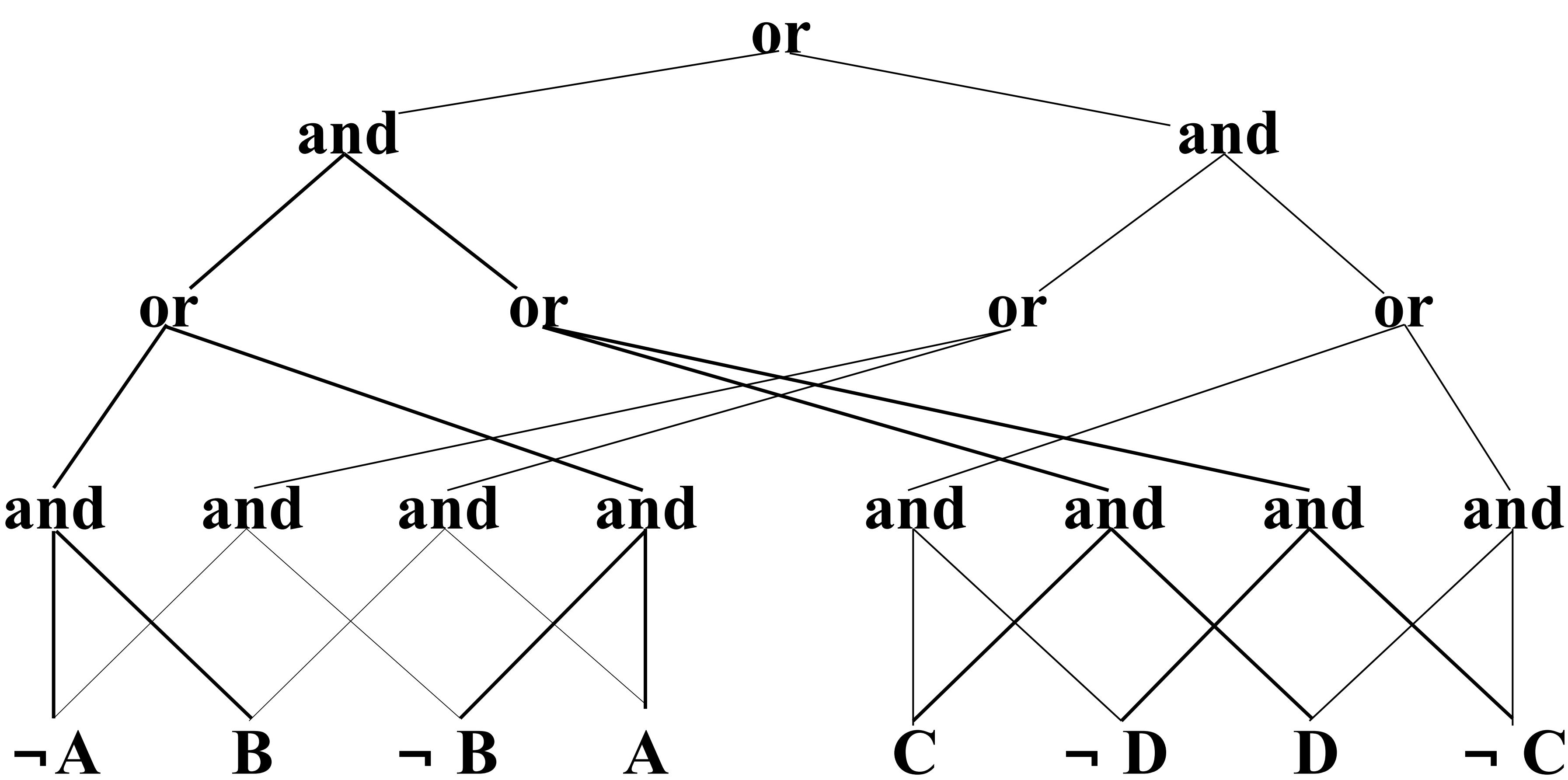


OBDD (NNF)

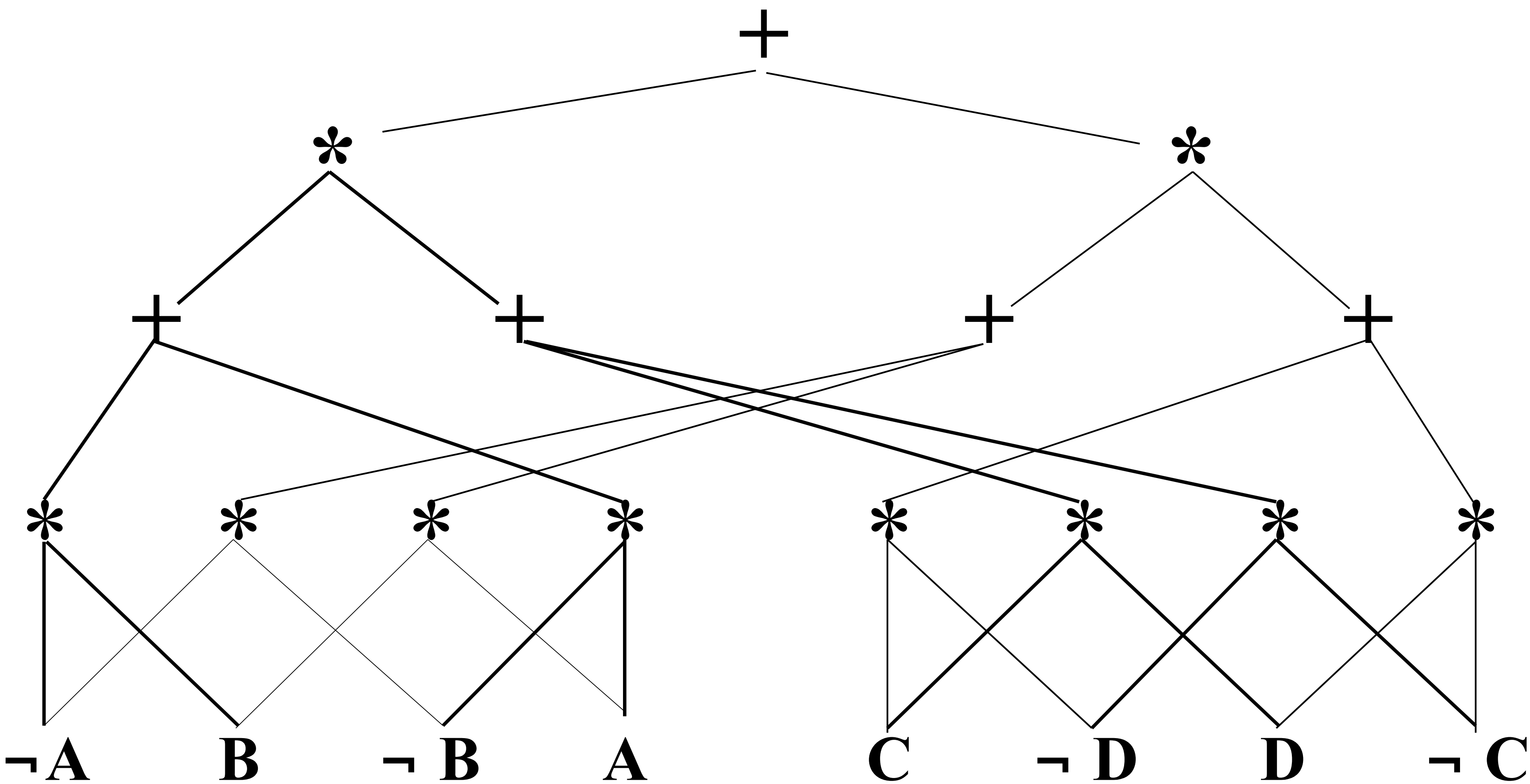
Queries and Transformations

- **Queries**
  SAT, MAXSAT, logical entailment, equivalence testing, model counting,…
- **Transformations:**
  Existential quantification, conjunction, disjunction, negation…
- More properties imply more polytime queries and transformations, but less succinctness

Counting Models (d-DNNF)

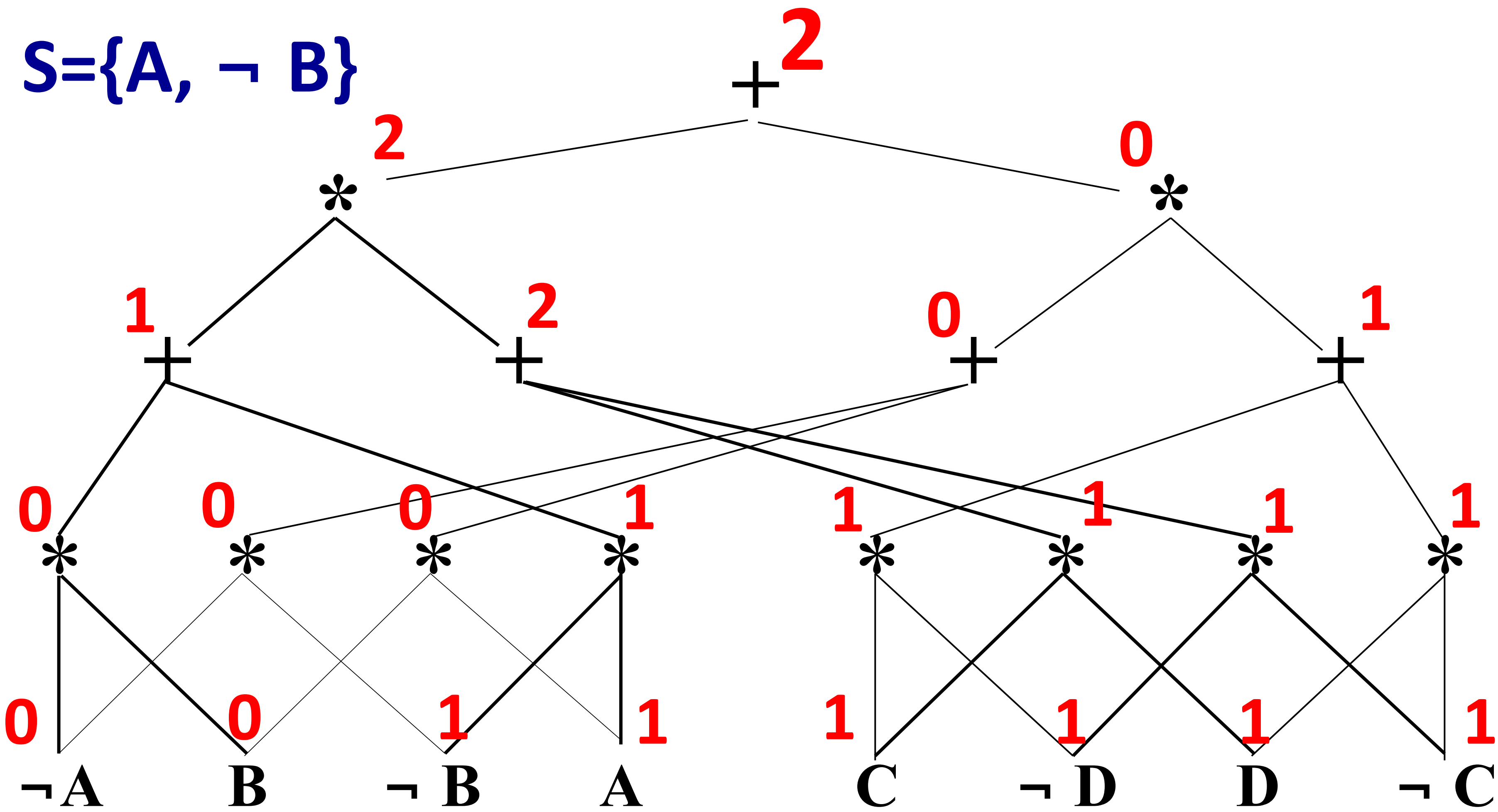


Counting Graph

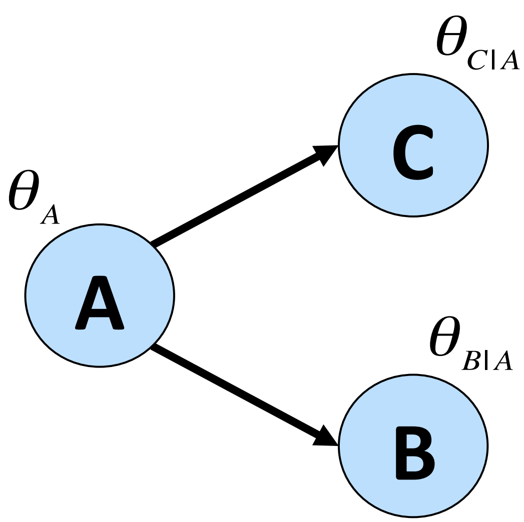


Counting Graph

S={A, ¬ B}



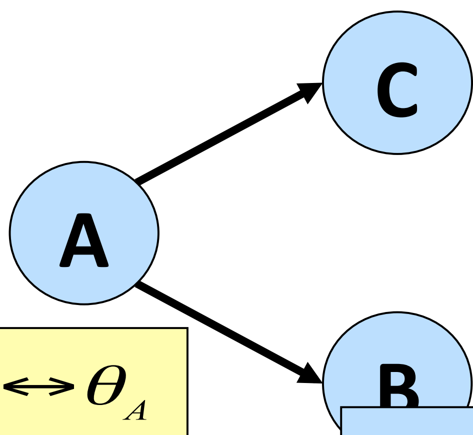
Probabilistic Inference by Weighted Model Counting



$\Pr(\neg B)$

A	B	C	Pr(.)
T	T	T	$\theta_A \theta_{B\|A} \theta_{C\|A}$
T	T	F	$\theta_A \theta_{B\|A} \theta_{\neg C\|A}$
T	F	T	$\theta_A \theta_{\neg B\|A} \theta_{C\|A}$
T	F	F	$\theta_A \theta_{\neg B\|A} \theta_{\neg C\|A}$
F	T	T	$\theta_{\neg A} \theta_{B\|\neg A} \theta_{C\|\neg A}$
F	T	F	$\theta_{\neg A} \theta_{B\|\neg A} \theta_{\neg C\|\neg A}$
F	F	T	$\theta_{\neg A} \theta_{\neg B\|\neg A} \theta_{C\|\neg A}$
F	F	F	$\theta_{\neg A} \theta_{\neg B\|\neg A} \theta_{\neg C\|\neg A}$

Probabilistic Inference by Weighted Model Counting



$A \leftrightarrow \theta_A$
$\neg A \leftrightarrow \theta_{\neg A}$

$A \wedge B \leftrightarrow \theta_{B|A}$

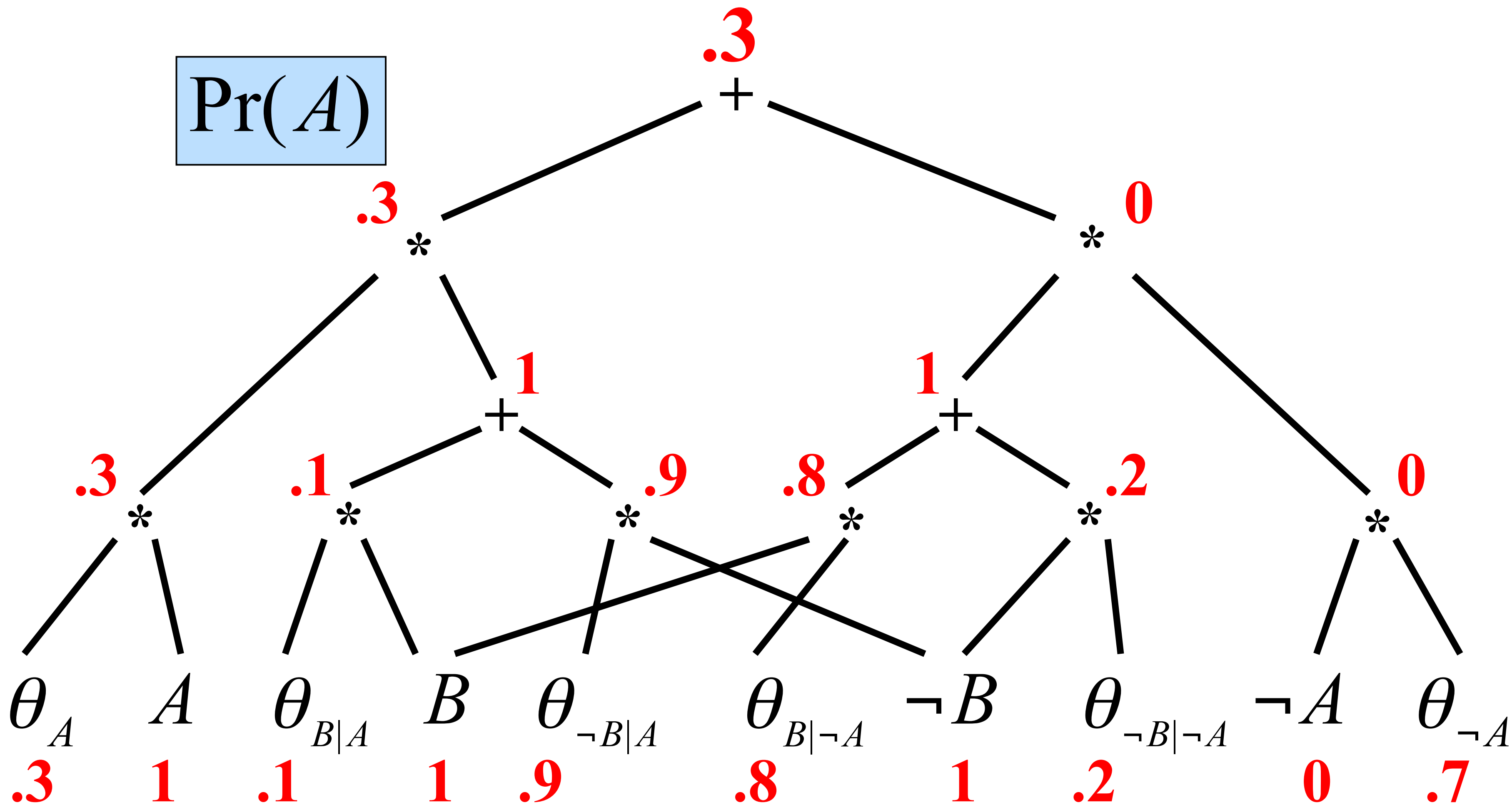
$A \wedge C \leftrightarrow \theta_{C|A}$
$A \wedge \neg C \leftrightarrow \theta_{\neg C|A}$
$\vdots$

A	B	C	Pr(.)
T	T	T	$\theta_A \theta_{B|A} \theta_{C|A}$
T	T	F	$\theta_A \theta_{B|A} \theta_{\neg C|A}$
T	F	T	$\theta_A \theta_{\neg B|A} \theta_{C|A}$
T	F	F	$\theta_A \theta_{\neg B|A} \theta_{\neg C|A}$

$$\Pr(\alpha) = wmc(\Delta \wedge \alpha)$$

$$A, B, \neg C \Rightarrow \underset{.3}{\theta_A}, \underset{.6}{\theta_{B|A}}, \underset{.8}{\theta_{\neg C|A}}, \underset{1}{\neg \theta_{\neg A}}, \ldots, \underset{1}{\neg \theta_{\neg C|\neg A}}$$

Weighted Model Counting (Arithmetic Circuits)



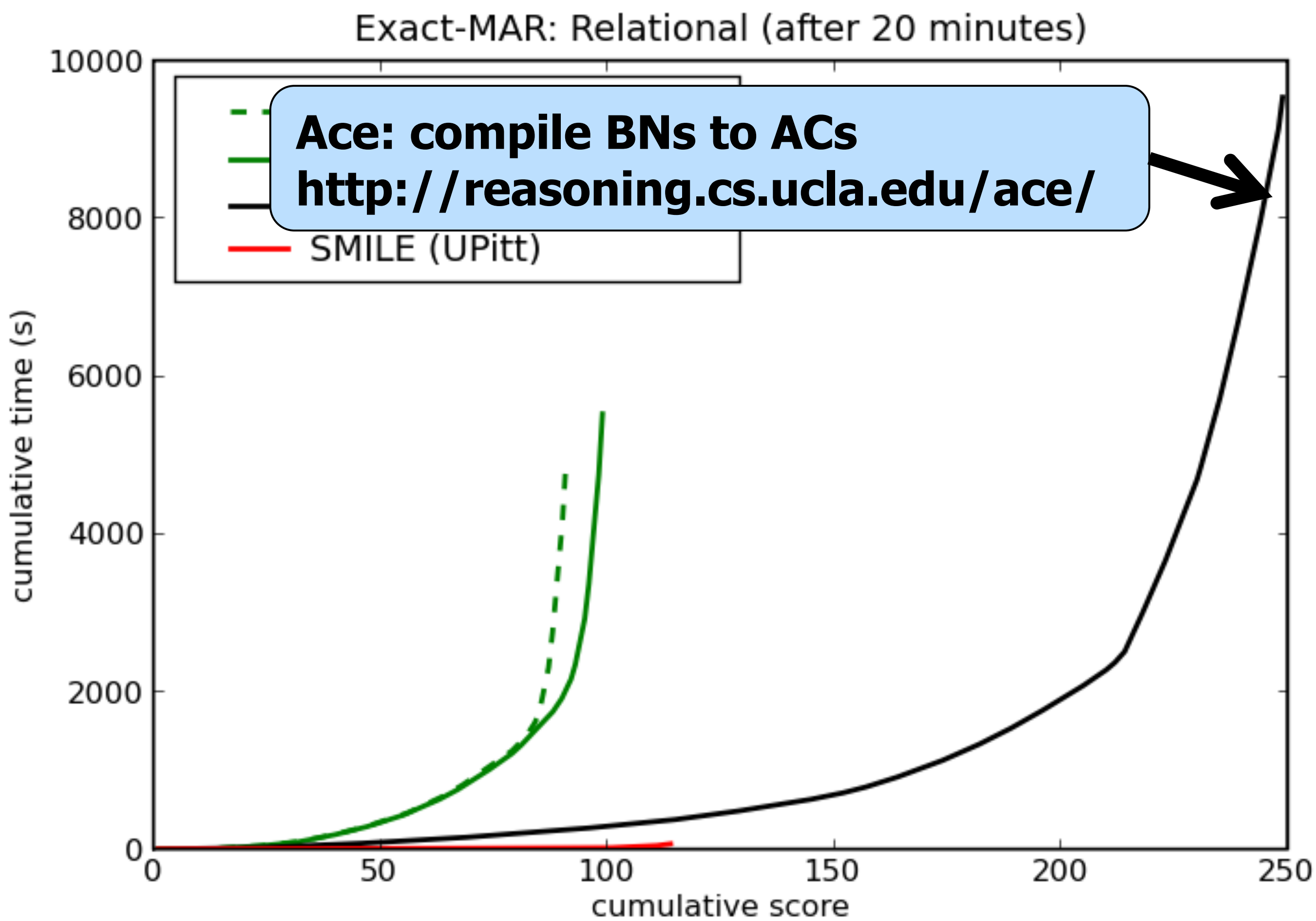
Why Logic?

- Encoding local structure is easy:
  - Zero-parameters encoded by adding clauses:

$$\boxed{\theta_{C|A}=0} \quad \boxed{\neg A \vee \neg C}$$

  - Context-specific independence encoded by collapsing variables:

$$\boxed{\theta_{C|AB}=\theta_{C|A\neg B}}$$



- Relational networks (251 networks)
  - Average clique size is 50

Alchemy - Open Source AI

Home

Documentation
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Developer's Manual
APIs
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FAQs

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Requ
Dow

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Alchemy
Alchemy-announce
Alchemy-update
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Code
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Publications

Contributors

Welcome to the Alchemy system! Alchemy is a software package providing a series of algorithms for statistical relational learning and probabilistic logic inference, based on the Markov logic representation. Alchemy allows you to easily develop a wide range of AI applications, including:

- Collective classification
- Link prediction
- Entity resolution
- Social network modeling
- Information extraction

If you are not already familiar with Markov logic, we recommend that you first read the paper Unifying Logical and Statistical AI.

Alchemy is a software package providing a series of algorithms for statistical relational learning and probabilistic logic inference, based on Markov logic representations.

- Generative weight learning
- Structure learning
- MAP/MPE inference (including memory efficient)
- Probabilistic inference: MC-SAT, Gibbs Sampling, Simulated Tempering, Belief Propagation (including lifted)
- Support for native and linked-in functions
- Block inference and learning over variables with mutually exclusive and exhaustive values
- EM (to handle ground atoms with unknown truth values during learning)
- Specification of indivisible formulas (i.e. formulas that should not be broken up into separate clauses)
- Support of continuous features and domains
- Online inference
- Decision Theory

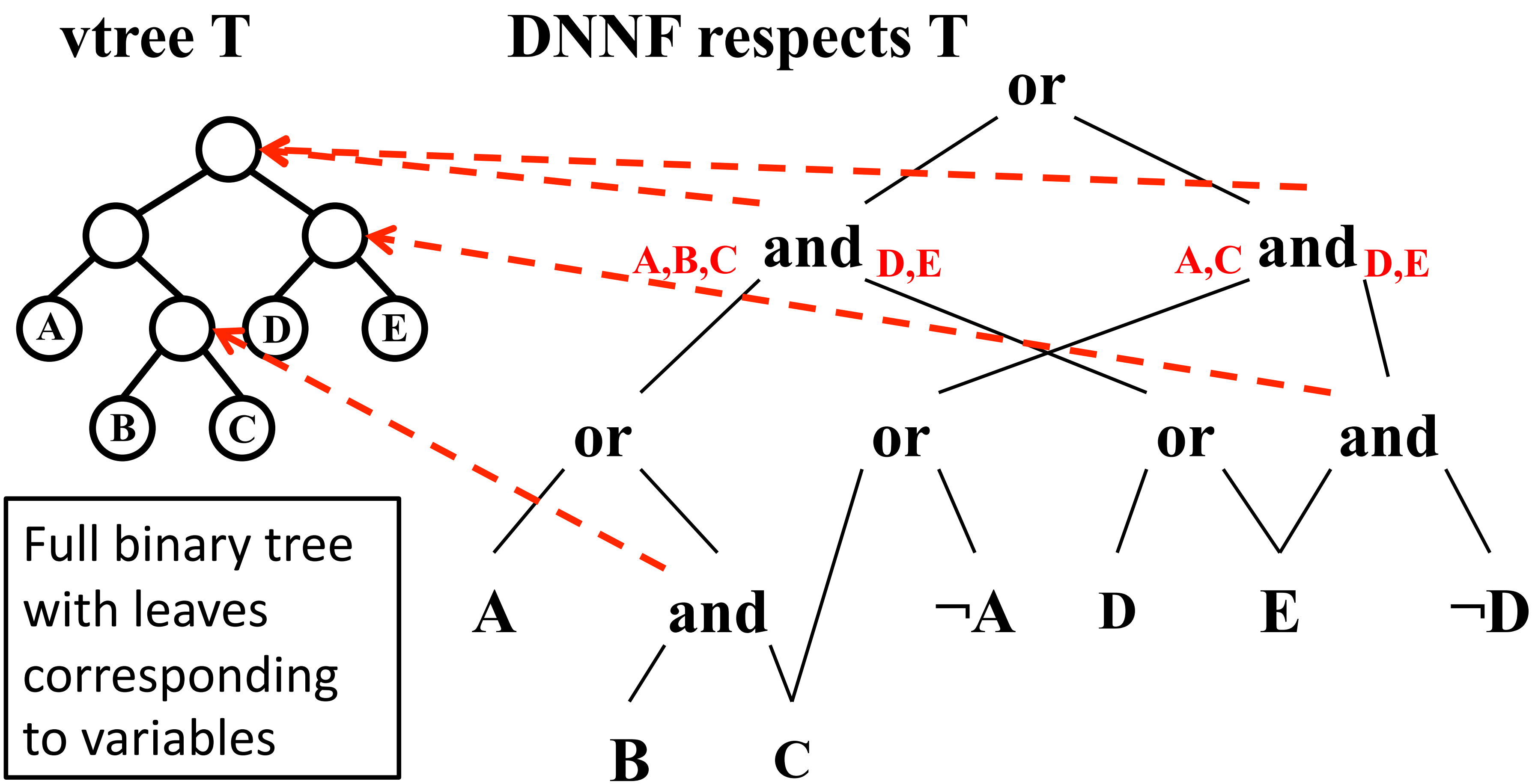
In the next release we plan to include:

- Online learning
- Exact inference for small domains

Current Challenges

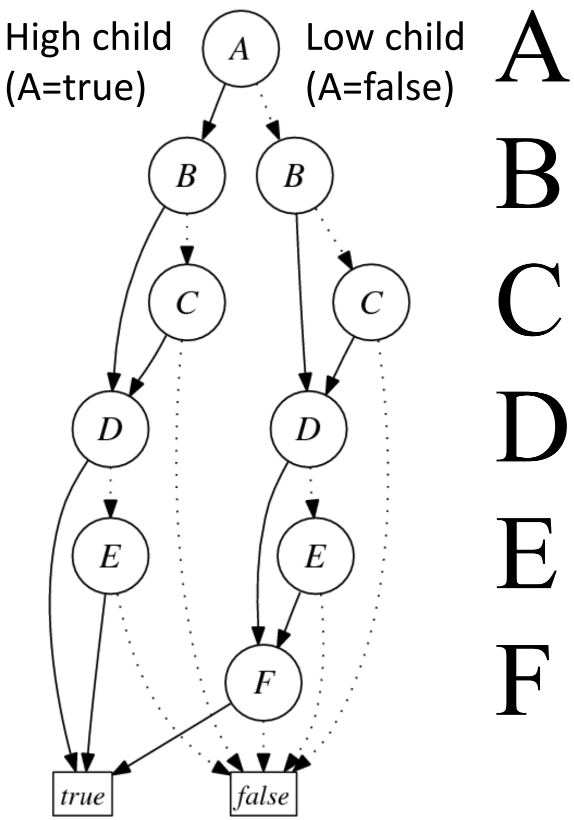
- **Incremental compilation:**
  - What? Current compilers monolithic: c2d (UCLA) and DSharp (Toronto)
  - Need:
    - Logic: planning and verification applications
    - Probability: approximate inference
  - Main insight:
    - Structured decomposability & vtrees (AAAI-08, AAAI-10)
- **Guarantees and Complexity results:**
  - Upper & lower bounds on size of compilation (AAAI-10, ECAI-10)
  - Main insights:
    - The notion of a decomposition (AAAI-10)
    - The notion of an interaction function (ECAI-10)

Structured Decomposability

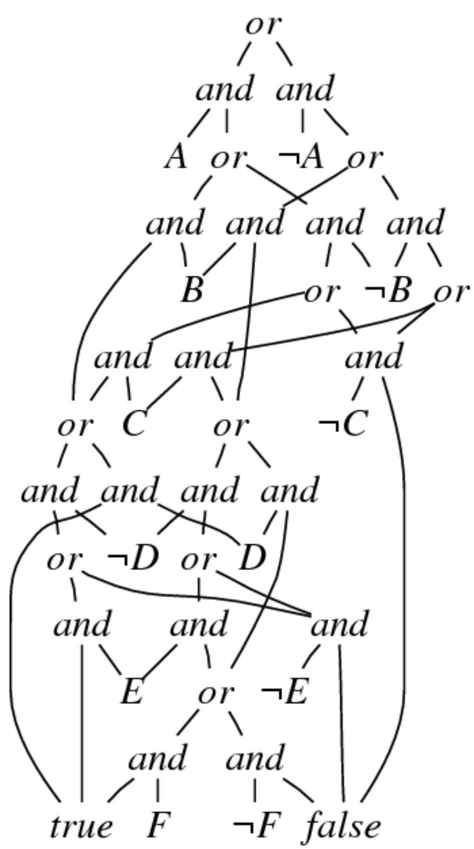


Full binary tree with leaves corresponding to variables

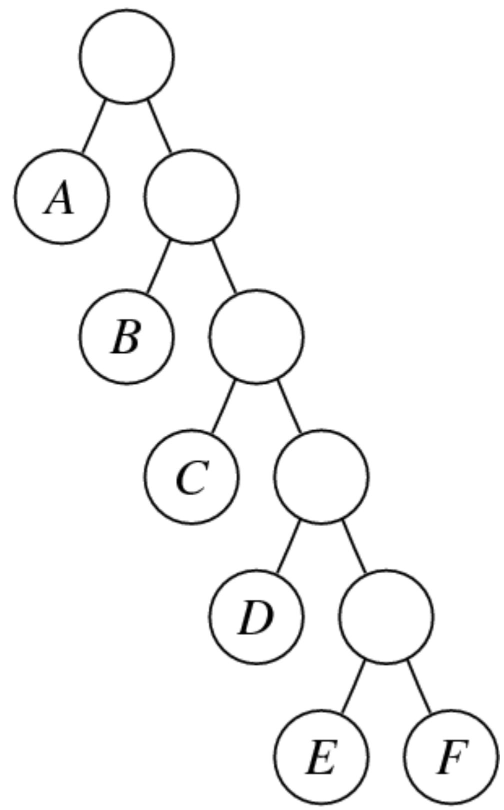
OBDD: DNNF that Respects Linear vtree



OBDD (traditional form)



OBDD (NNF)



Linear vtree

Decomposition of Boolean Functions (AAAI-10)

- Examples: $f = (X_1 \vee X_2) \wedge (Y_1 \vee X_2) \wedge (X_1 \vee Y_2) \wedge (Y_1 \vee Y_2) \vee (X_2 \wedge Y_3)$
  - $\mathbf{X} = \{X_1, X_2\}$, $\mathbf{Y} = \{Y_1, Y_2, Y_3\}$:

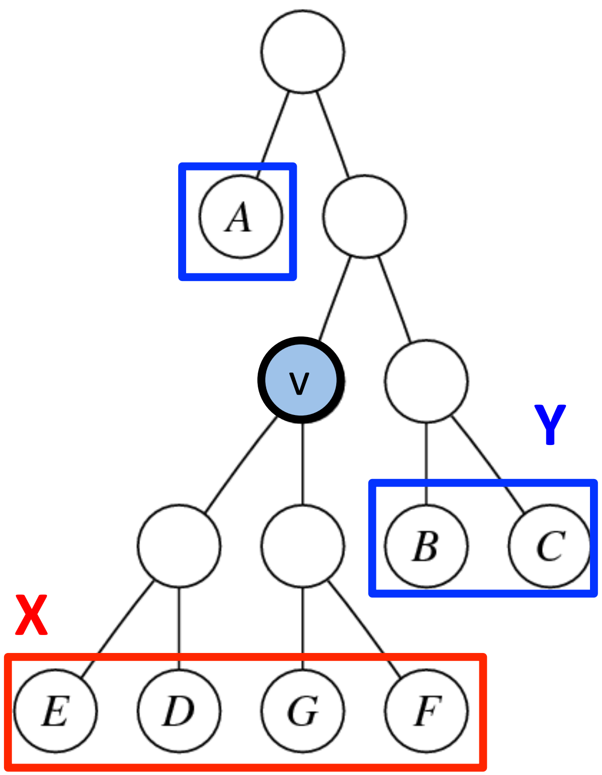
$$\cancel{f(\mathbf{X},\mathbf{Y}) = g(\mathbf{X}) \wedge h(\mathbf{Y})}$$

$$f(\mathbf{X},\mathbf{Y}) = \underbrace{f_1}_{g_1(\mathbf{X}) \wedge h_1(\mathbf{Y})} \vee \underbrace{f_2}_{g_2(\mathbf{X}) \wedge h_2(\mathbf{Y})} \vee \underbrace{f_3}_{g_3(\mathbf{X}) \wedge h_3(\mathbf{Y})} \vee \dots \vee \underbrace{f_m}_{g_m(\mathbf{X}) \wedge h_m(\mathbf{Y})}$$

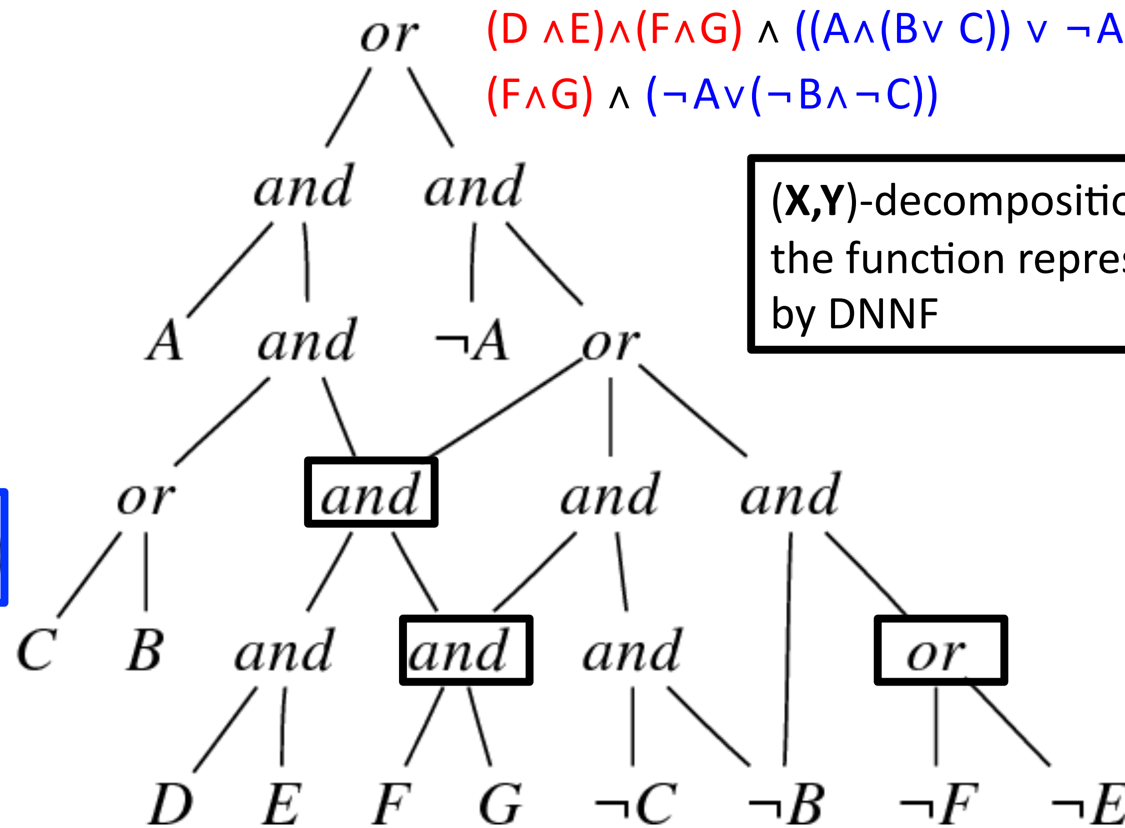
$$\boxed{(\mathbf{X},\mathbf{Y})\text{-decomposition of } f}$$

Lower Bounds (AAAI-10)

Vtree



DNNF



$(\neg E \vee \neg F) \wedge (\neg A \wedge \neg B)$ **∨**

$(D \wedge E) \wedge (F \wedge G) \wedge ((A \wedge (B \vee C)) \vee \neg A)$ **∨**

$(F \wedge G) \wedge (\neg A \vee (\neg B \wedge \neg C))$

(**X,Y**)-decomposition of the function represented by DNNF

The Interaction Function (ECAI-10)

$$f(\mathbf{X},\mathbf{Y}) = g(\mathbf{X}) \wedge h(\mathbf{Y}) \wedge I(\mathbf{X},\mathbf{Y})$$

Captures precisely knowledge about variables in **X**

$\exists \mathbf{Y}\, f$

Captures precisely knowledge about variables in **Y**

$\exists \mathbf{X}\, f$

Captures precisely interaction between variables **X** and **Y**

$\boxed{f \vee \neg(\exists \mathbf{X}\, f) \vee \neg(\exists \mathbf{Y}\, f)}$

The Interaction Function (ECAI-10)

$$f(\mathbf{X},\mathbf{Y}) = \quad g(\mathbf{X}) \wedge h(\mathbf{Y}) \wedge I(\mathbf{X},\mathbf{Y})$$

Captures precisely knowledge about variables in **X**

Captures precisely knowledge about variables in **Y**

Captures precisely interaction between variables **X** and **Y**

$\exists \mathbf{Y}\ f$

true

$\exists \mathbf{X}\ f$

(B v C)

A => (C => B)
¬A => (B => C)

(A => B) (¬A => C) **X**={A} **Y**={B,C}

Current Research

- Searching for good vtrees (on-going)
- Characterizing and searching for optimal decompositions
- Upper and lower bounds on size of DNNF

- Key objective: incremental compiler for DNNF and d-DNNF

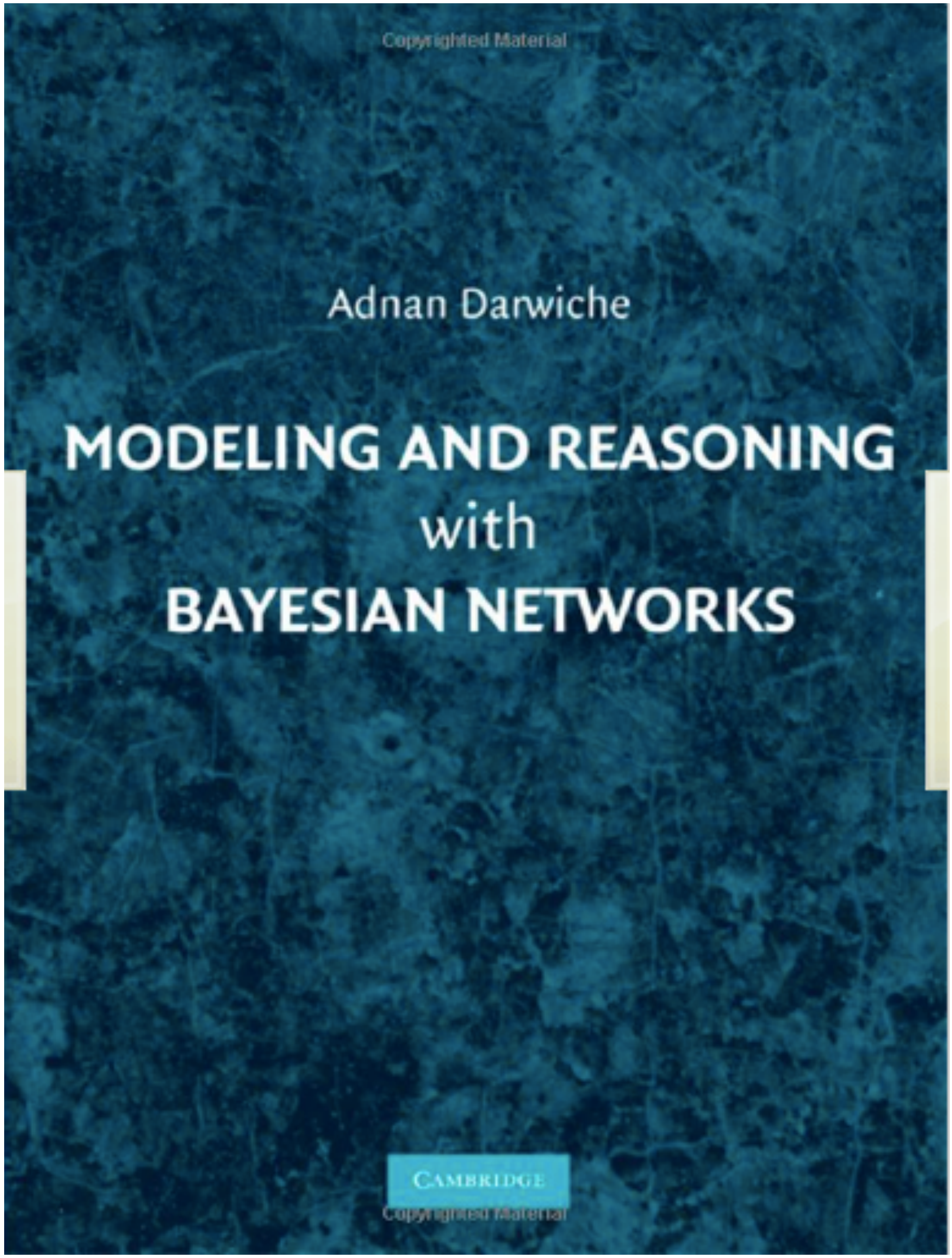
- ???

Two Main Themes

- **Exact inference as:**
  Enforcing decomposability and determinism on propositional knowledge bases

- **Approximate inference as:**
  Relaxing, compensating for, and recovering equivalence constraints (equalities)

http://reasoning.cs.ucla.edu/samiam/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Two Main Themes

- **Exact inference as:**
  Enforcing decomposability and determinism on propositional knowledge bases

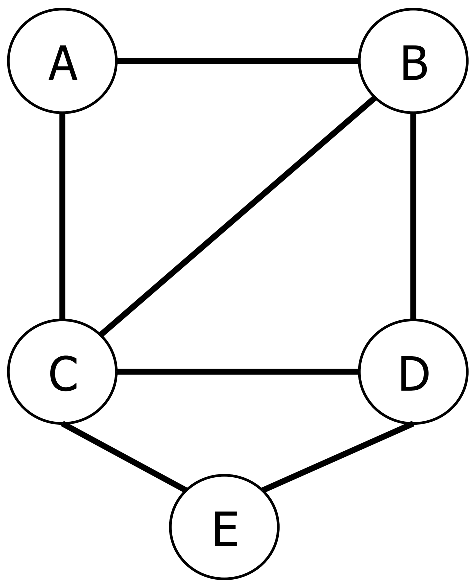
- **Approximate inference as:**
  Relaxing, compensating for, and recovering equivalence constraints (equalities)

Treewidth

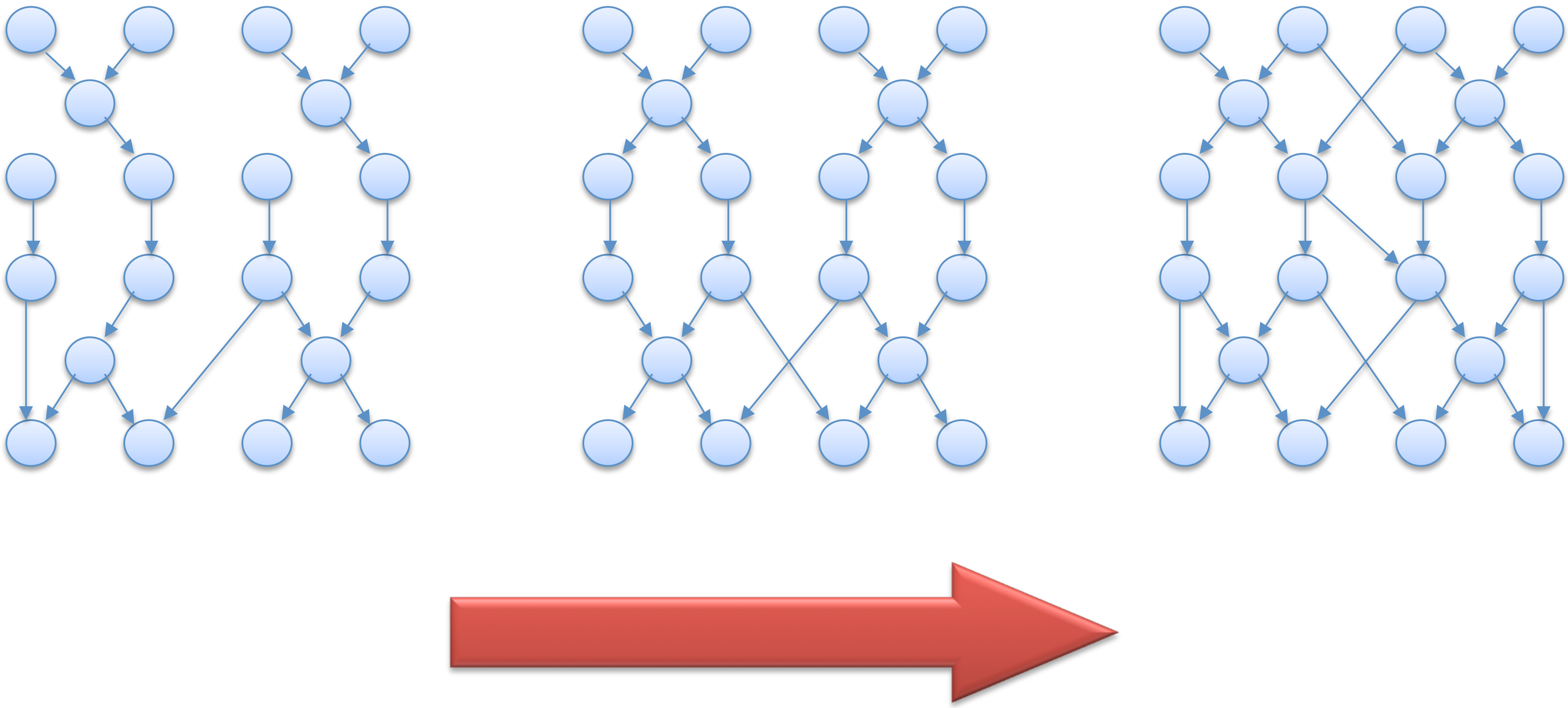
CNF

$(A \vee B \vee \neg C) \wedge$
$(A \vee \neg B \vee C) \wedge$
$(C \vee \neg D \vee E) \wedge$
$(B \vee D) \wedge$
$(D \vee E)$

Constraint Graph



Treewidth



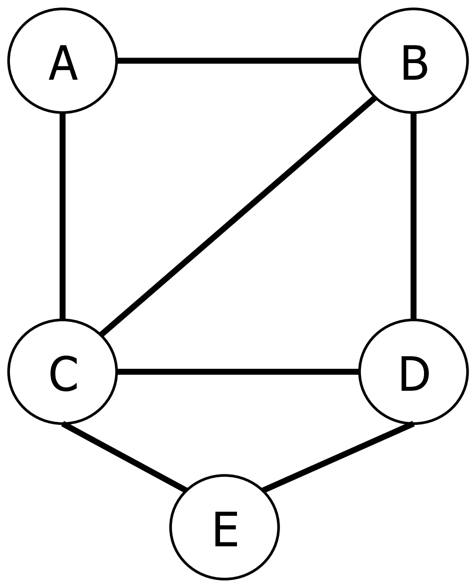
$$O(n \exp\{w\})$$

Treewidth

CNF

(A v B v ¬ C) ∧
(A v ¬ B v C) ∧
(C v ¬ D v E) ∧
(B v D) ∧
(D v E)

Constraint Graph

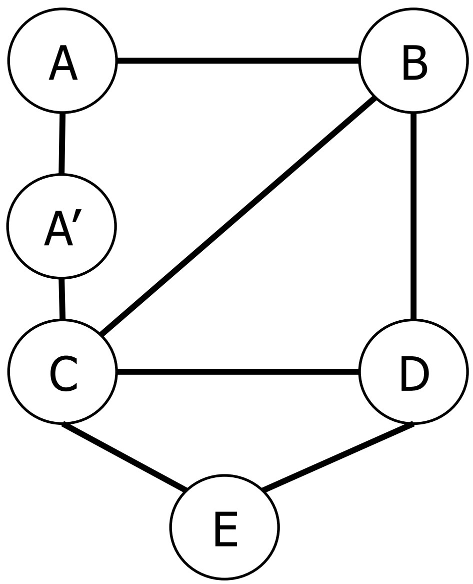


Treewidth

CNF

$(A \vee B \vee \neg C) \wedge$
$(A' \vee \neg B \vee C) \wedge$
$(C \vee \neg D \vee E) \wedge$
$(B \vee D) \wedge$
$(D \vee E) \wedge$
$(A = A')$

Constraint Graph

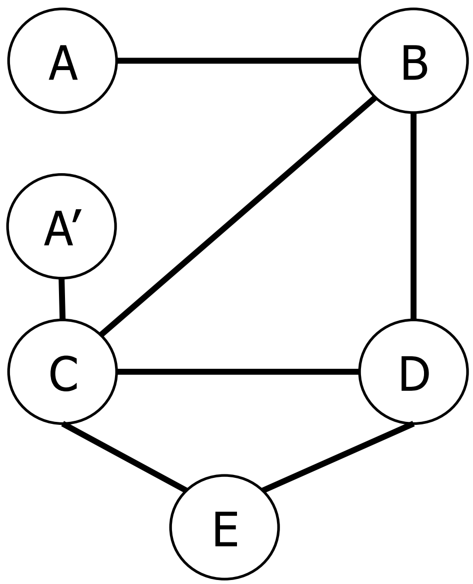


Treewidth

CNF

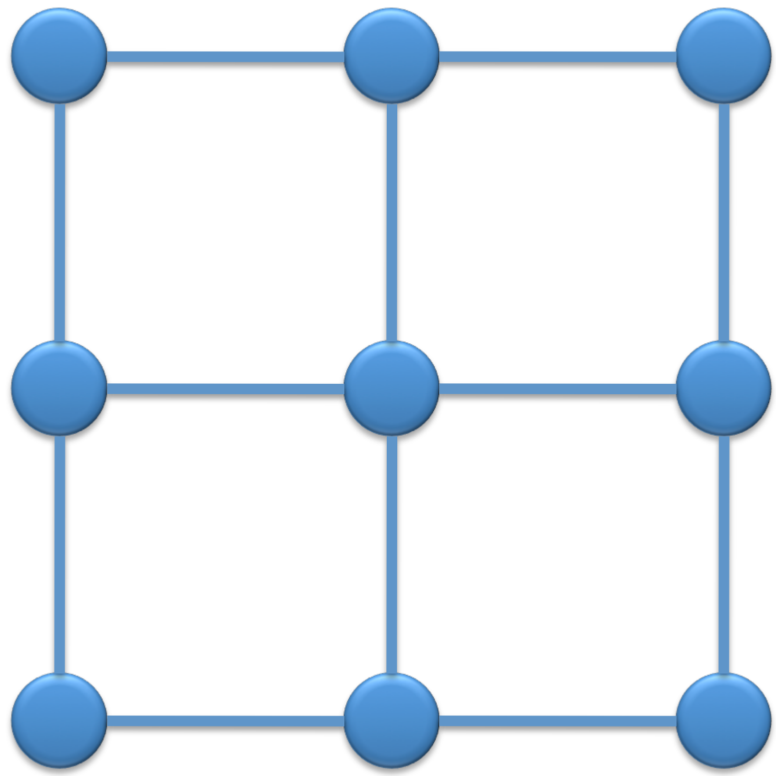
$(\mathbf{A} \vee B \vee \neg C) \wedge$
$(\mathbf{A'} \vee \neg B \vee C) \wedge$
$(C \vee \neg D \vee E) \wedge$
$(B \vee D) \wedge$
$(D \vee E)$

Constraint Graph



Equivalence Constraints

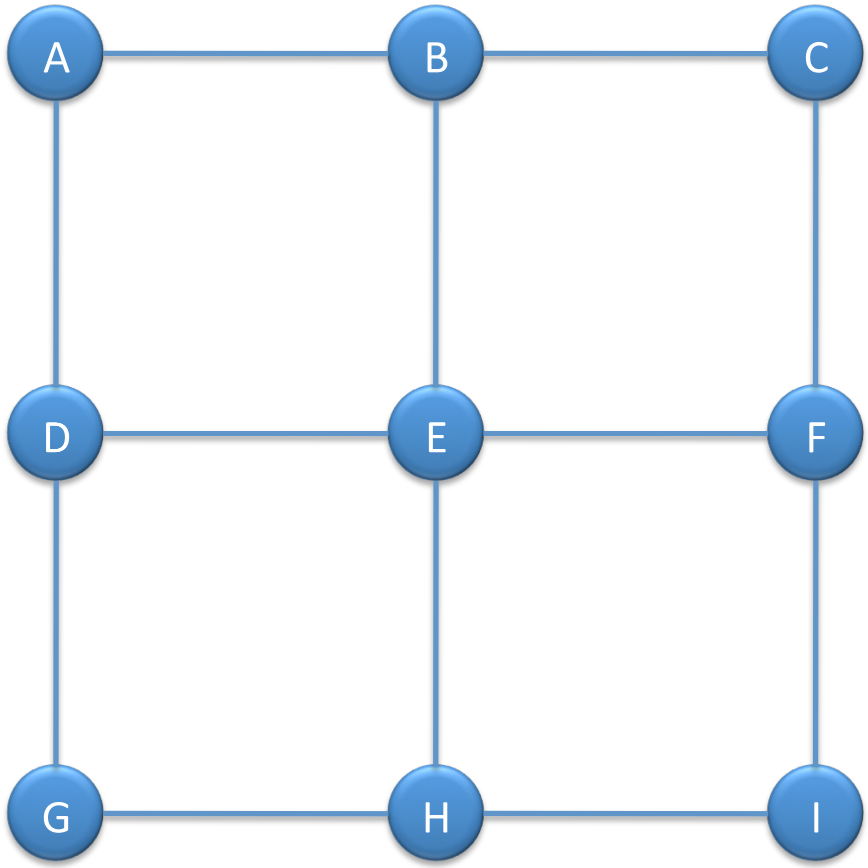
$$\psi_{eq}(X_i{=}x_i, X_j{=}x_j) = \begin{cases} 1 & \text{if } x_i = x_j \\ 0 & \text{otherwise} \end{cases}$$



$$\Pr(x_1, \ldots, x_n) = \frac{1}{Z} \psi(x_1, x_5) \ldots \psi(x_2, x_4) \ldots \theta(x_1) \ldots \theta(x_n)$$

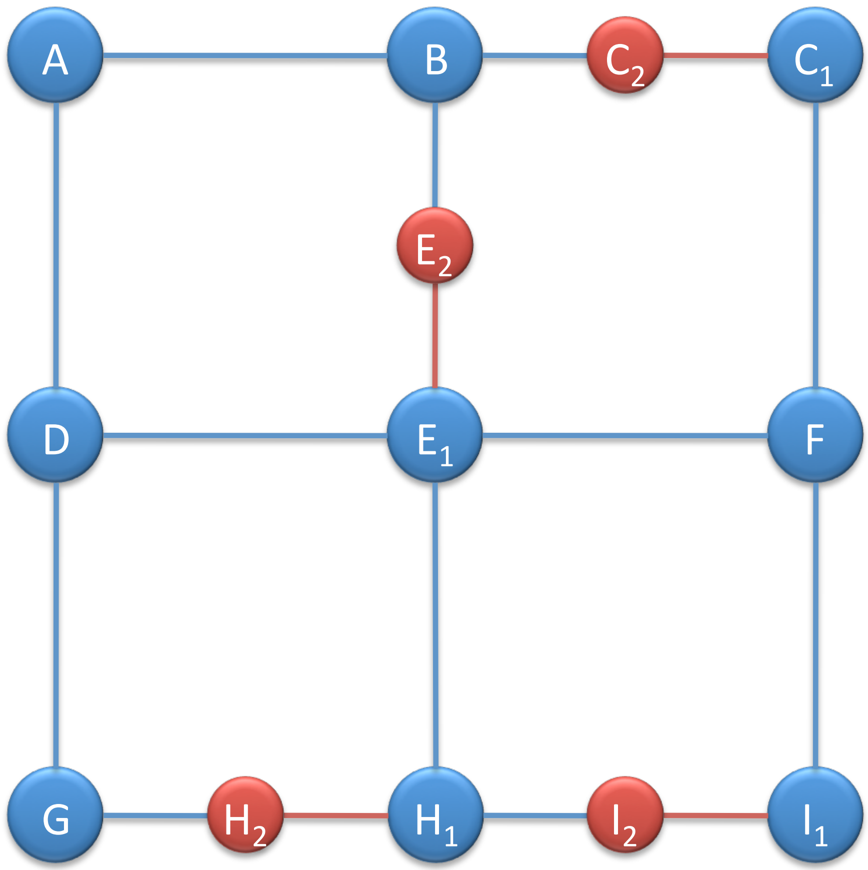
Relaxing Equivalence Constraints

- Model $\mathcal{M}$



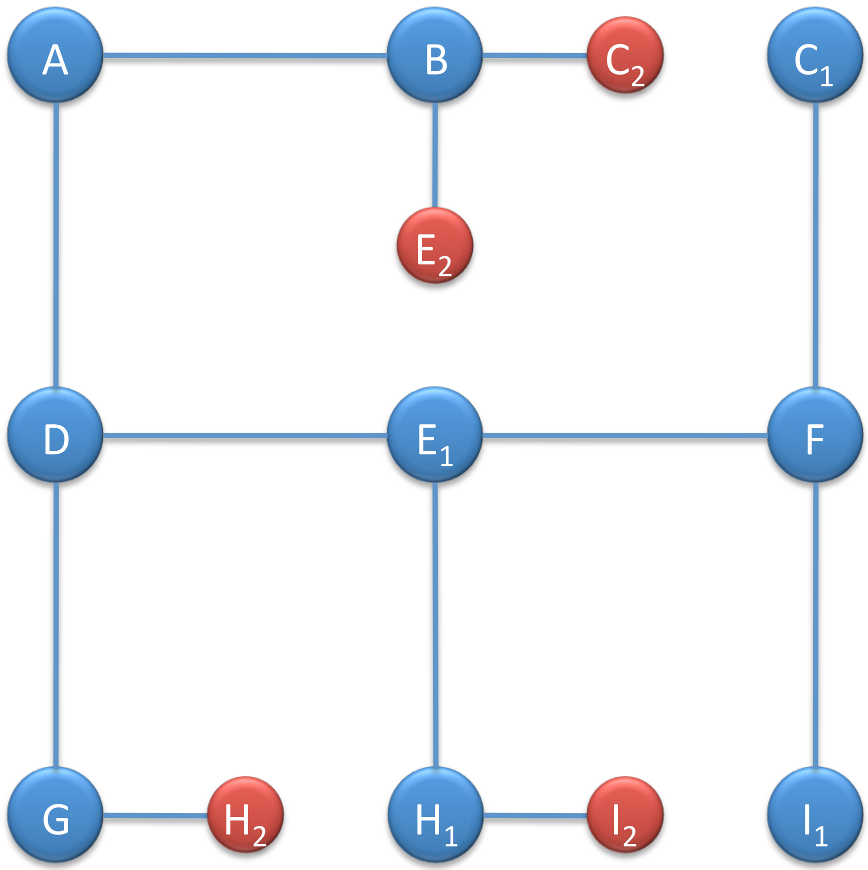
Relaxing Equivalence Constraints

- Model + Eq.



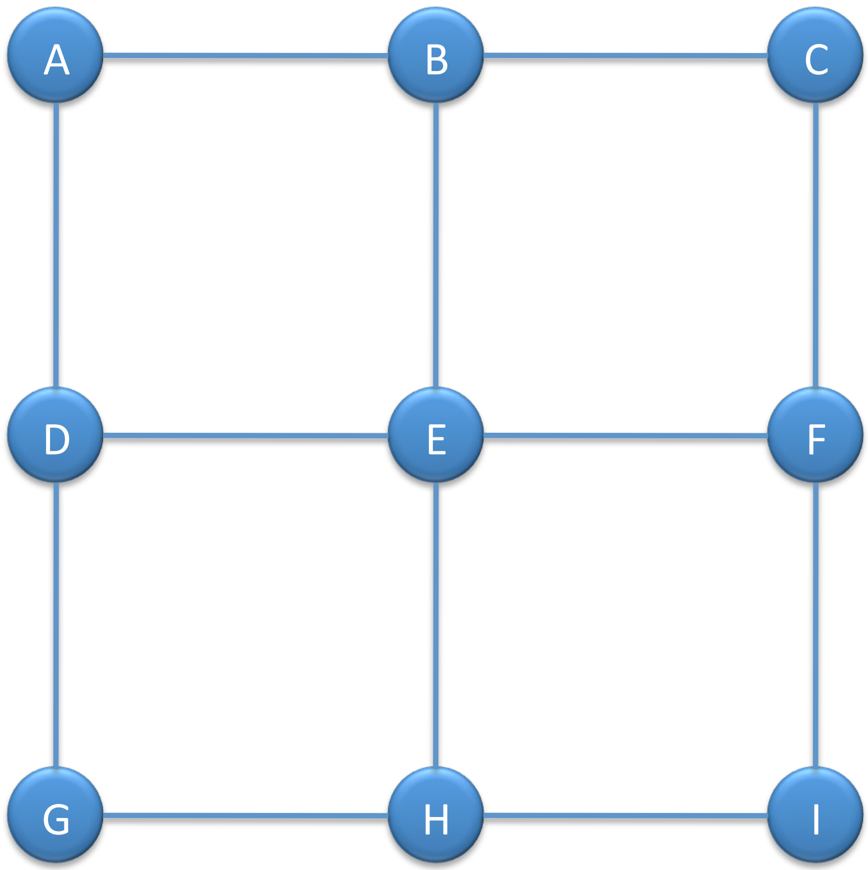
Relaxing Equivalence Constraints

- Relaxed
- Treewidth 1



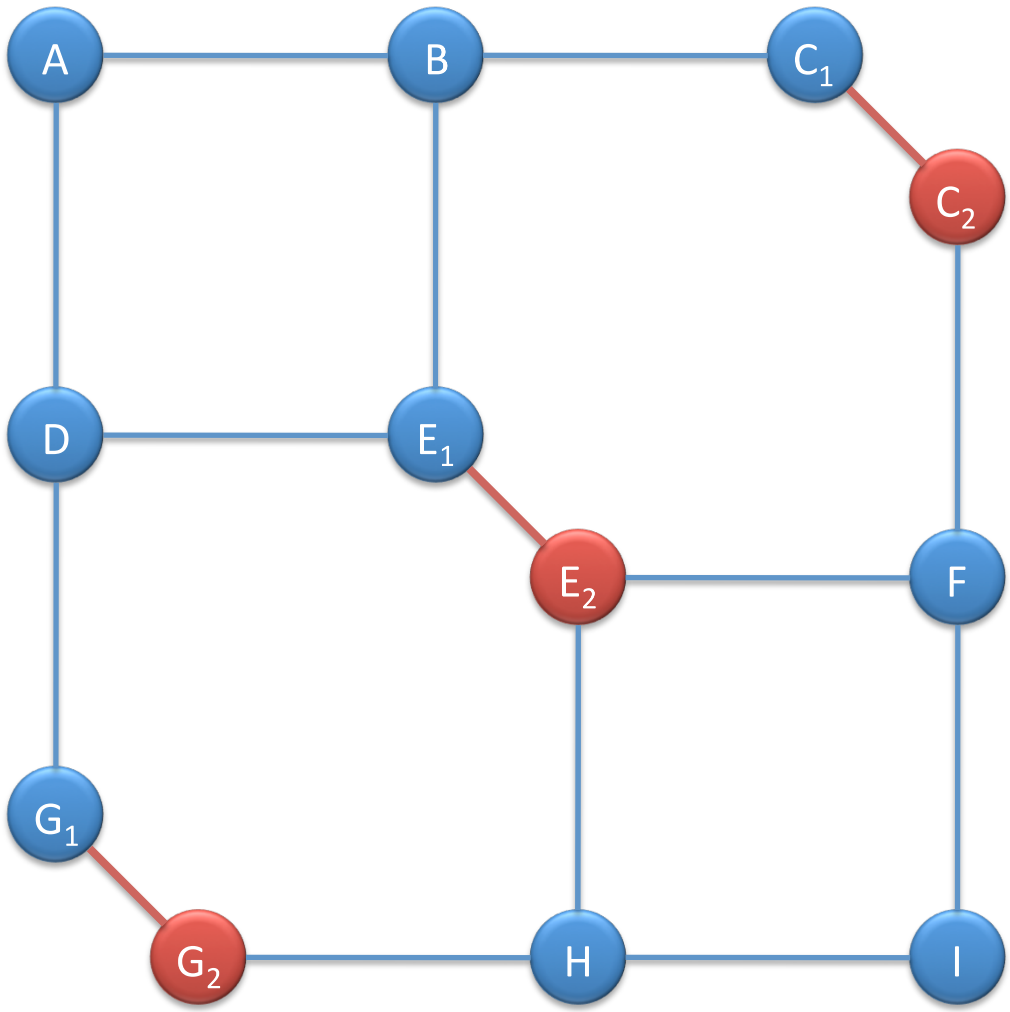
Relaxing Equivalence Constraints

- Model $\mathcal{M}$



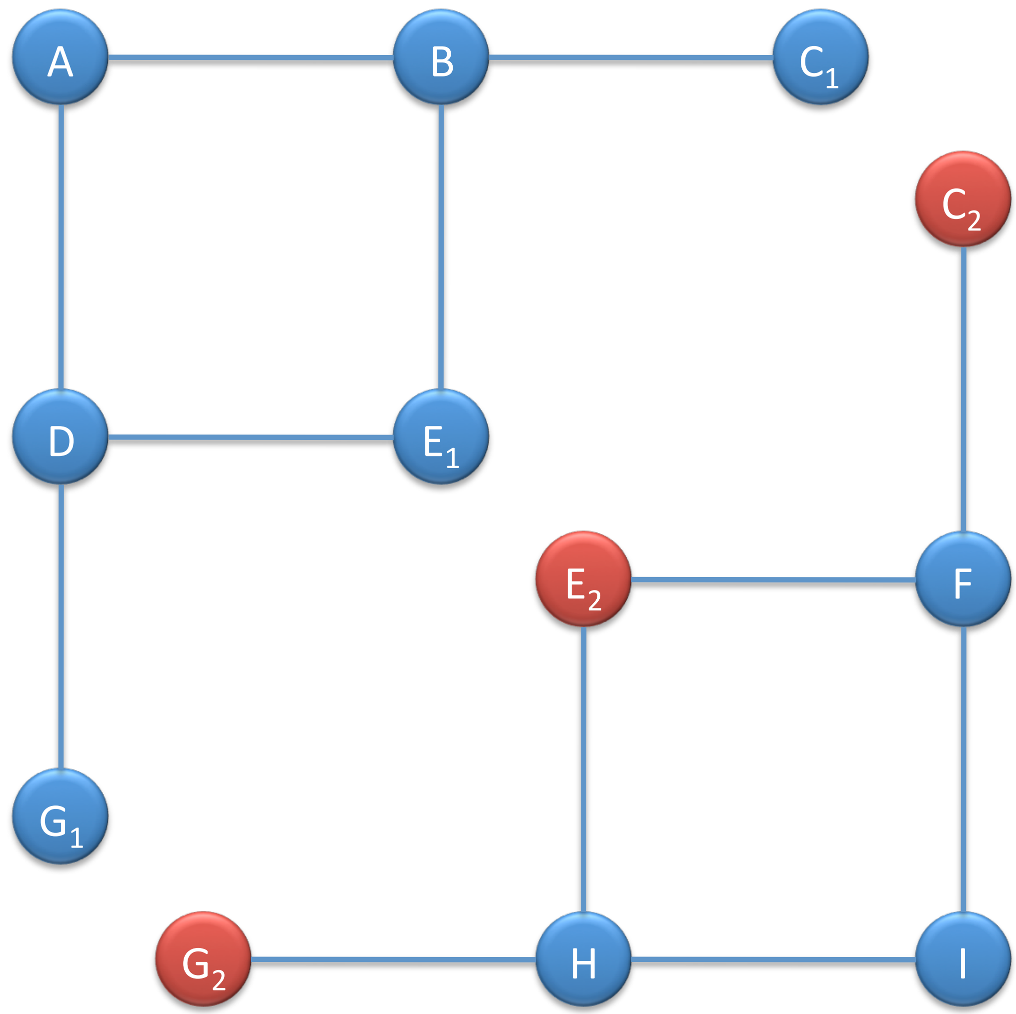
Relaxing Equivalence Constraints

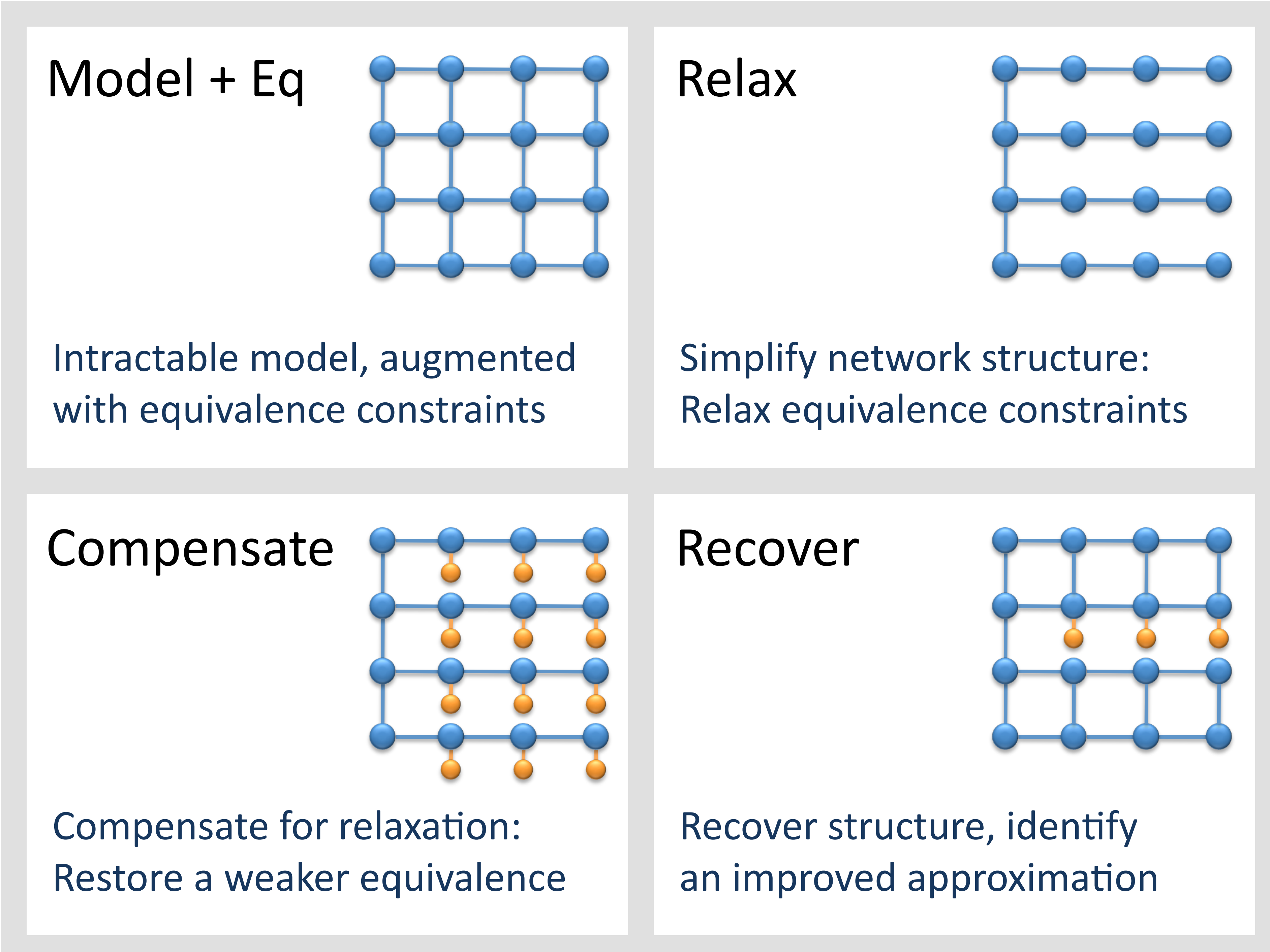
- Model + Eq.



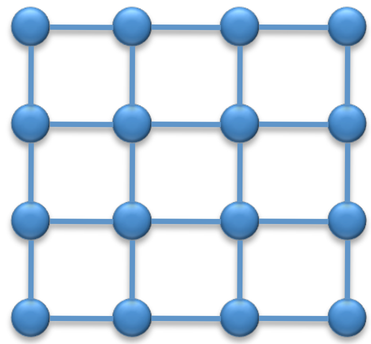
Relaxing Equivalence Constraints

- Relaxed
- Decomposed



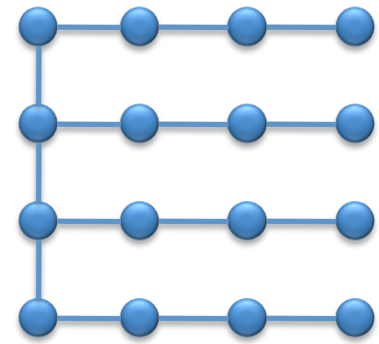

Model + Eq
Intractable model, augmented
with equivalence constraints
Relax
Simplify network structure:
Relax equivalence constraints
Compensate
Compensate for relaxation:
Restore a weaker equivalence
Recover
Recover structure, identify
an improved approximation

Model + Eq



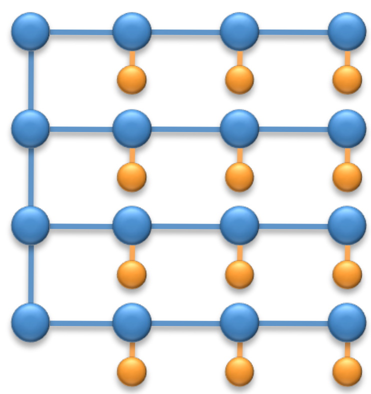
Intractable model, augmented with equivalence constraints

Relax



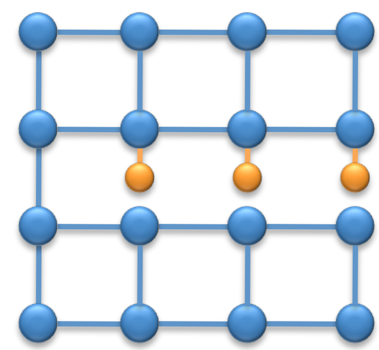
Usually gives upper/lower bounds: mini-buckets, MAXSAT

Compensate



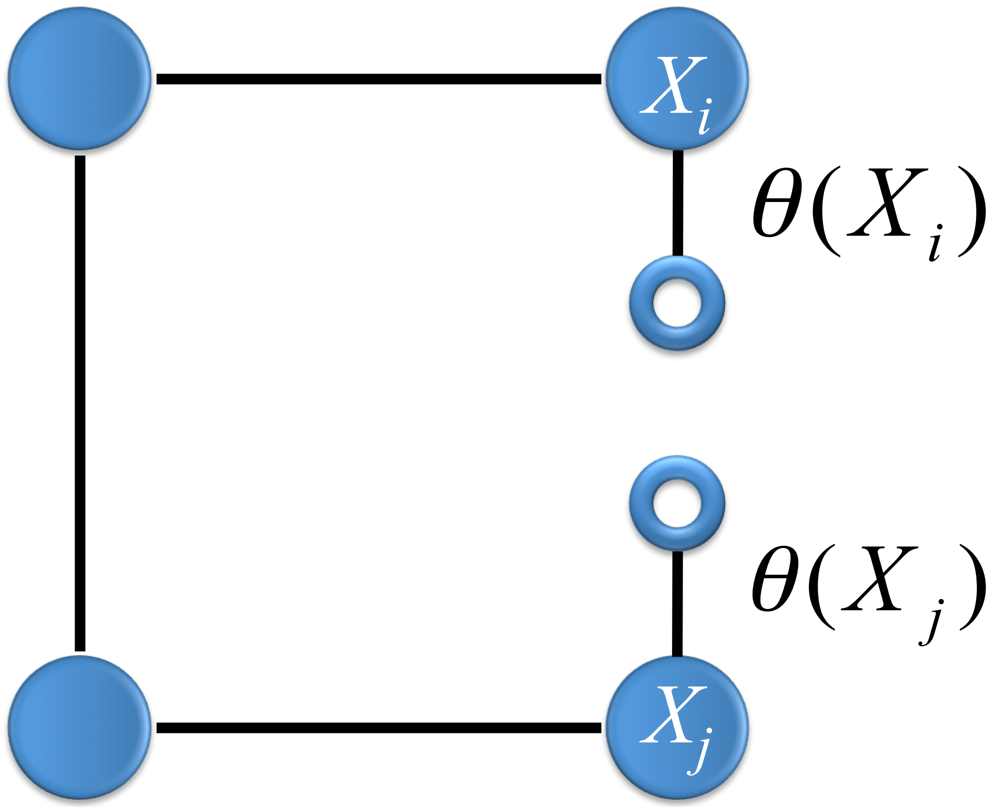
Compensate for relaxation: Restore a weaker equivalence

Recover



Recover structure, identify an improved approximation

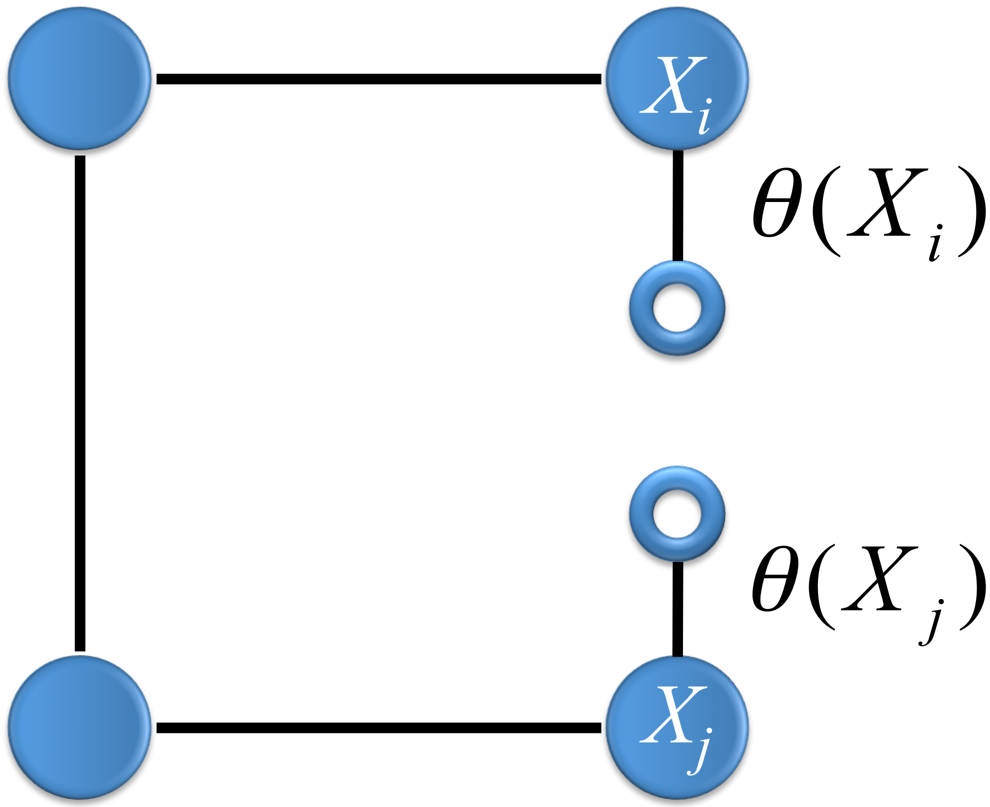
Compensating for an Equivalence



X_i	$\theta(X_i)$
T	.4789
F	.5211

X_j	$\theta(X_j)$
T	.8273
F	.1727

Compensating for an Equivalence

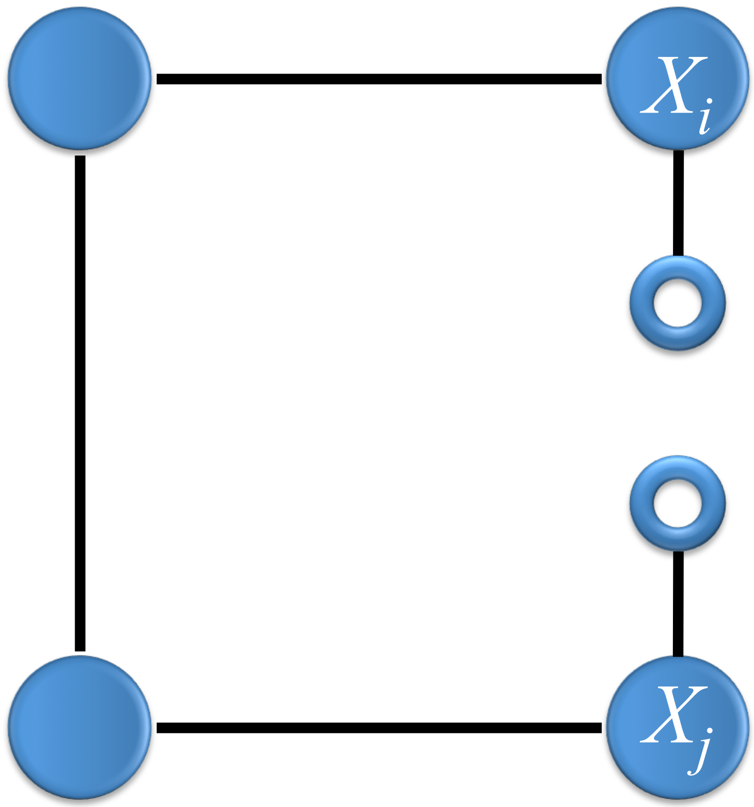


X_i	$\theta(X_i)$
T	.4789
F	.5211

X_j	$\theta(X_j)$
T	.8273
F	.1727

$$\Pr(X_i = x) = \Pr(X_j = x)$$

Compensating for an Equivalence

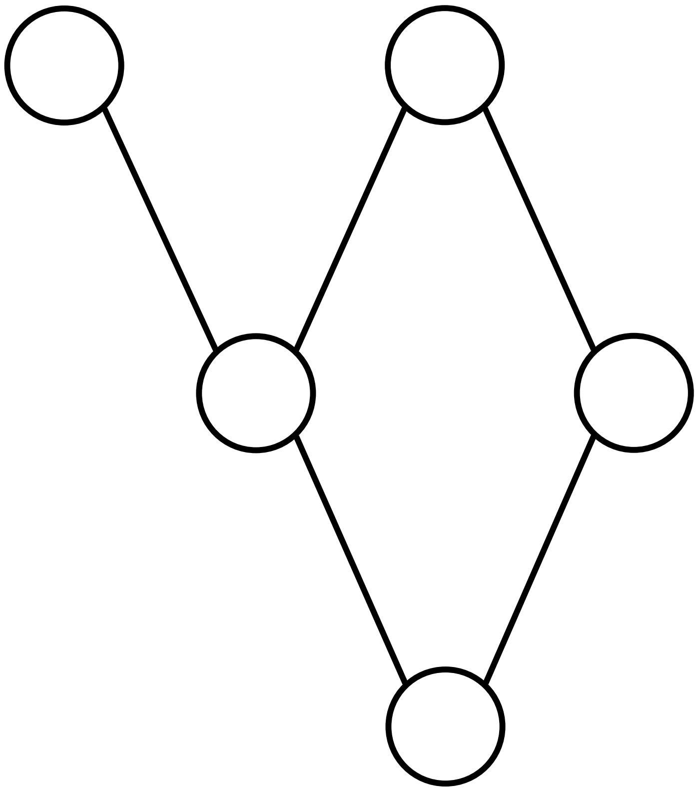


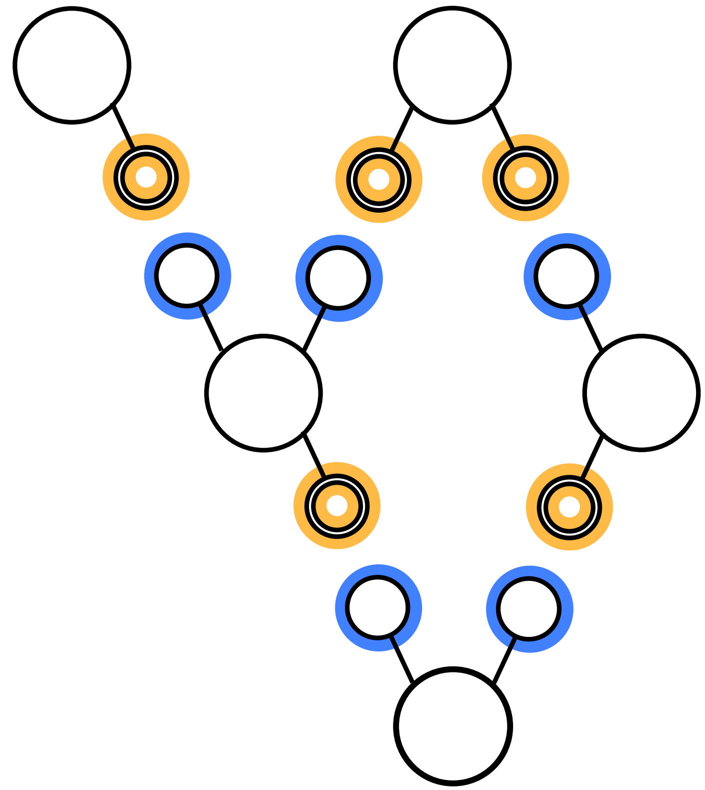
$$\theta(X_i) = \alpha \frac{\partial Z}{\partial \theta(X_j)}$$

$$\theta(X_j) = \alpha \frac{\partial Z}{\partial \theta(X_i)}$$

$$\Pr(X_i = x) = \Pr(X_j = x)$$

Parametrizing Edges Iteratively

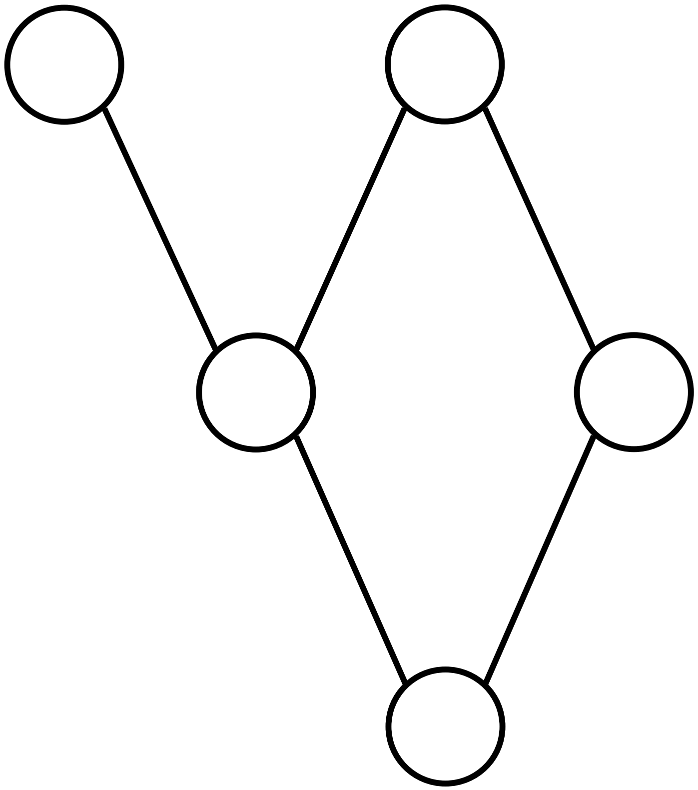


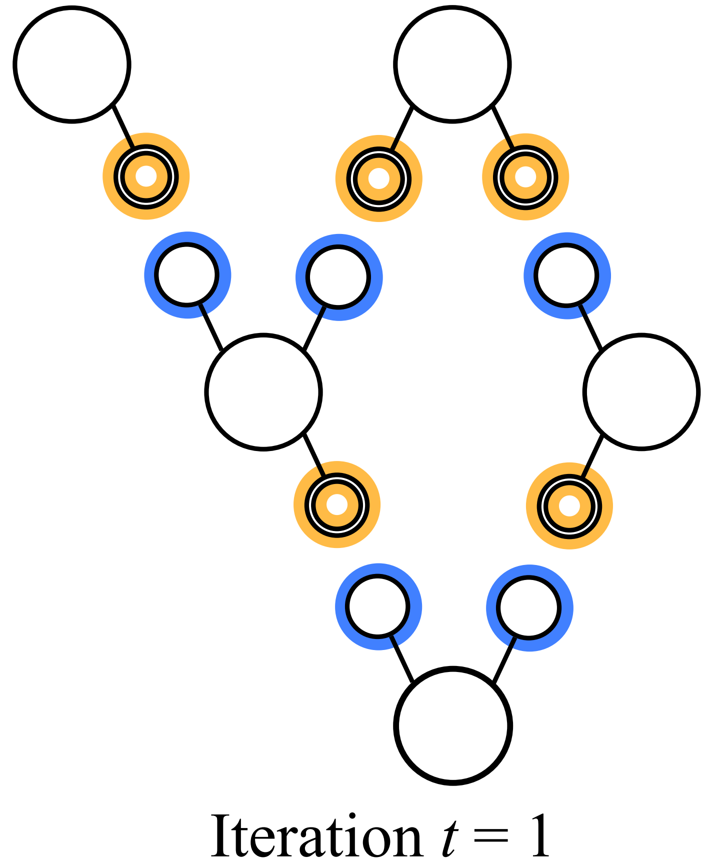


Iteration $t = 0$

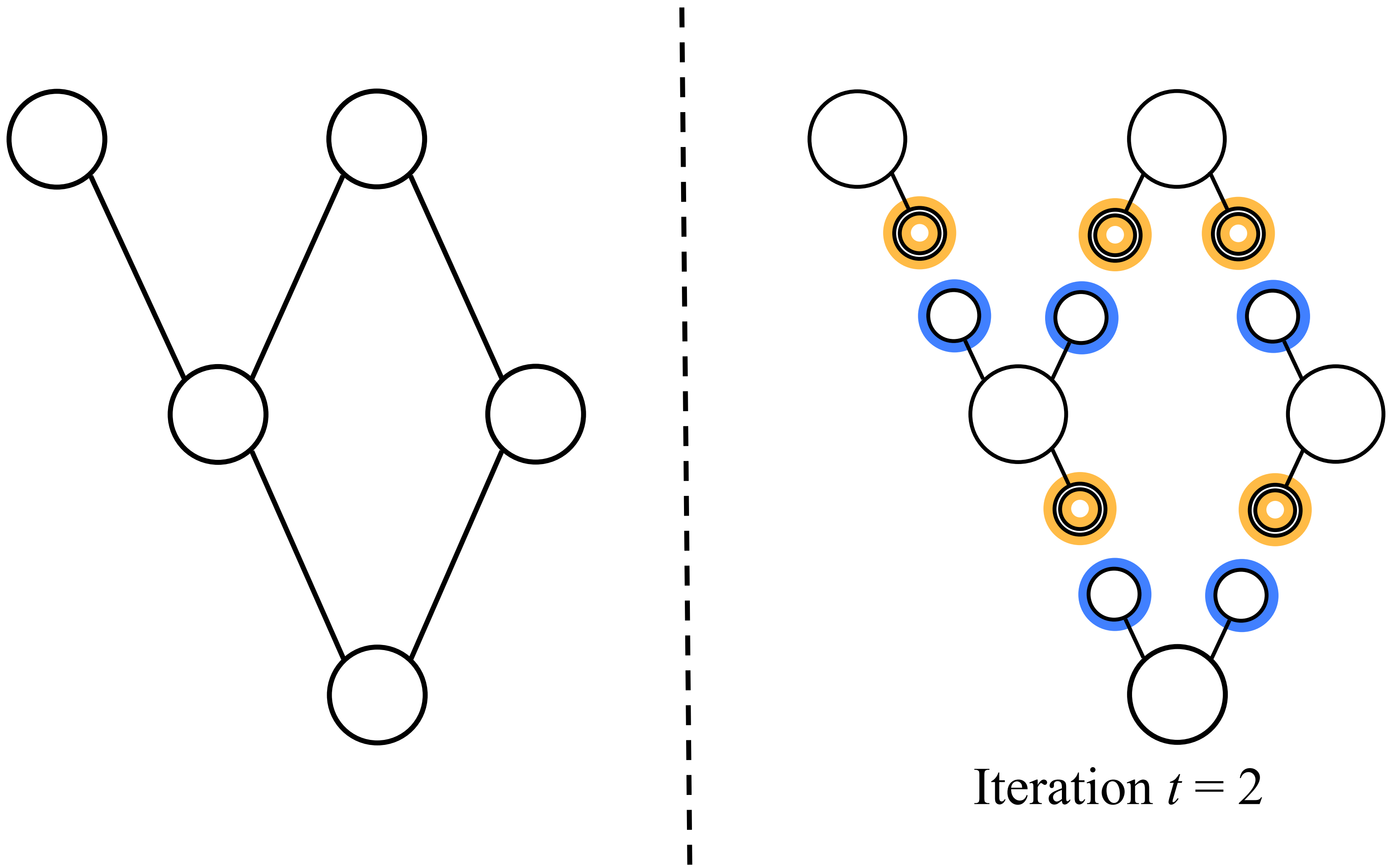
Initialization

Parametrizing Edges Iteratively



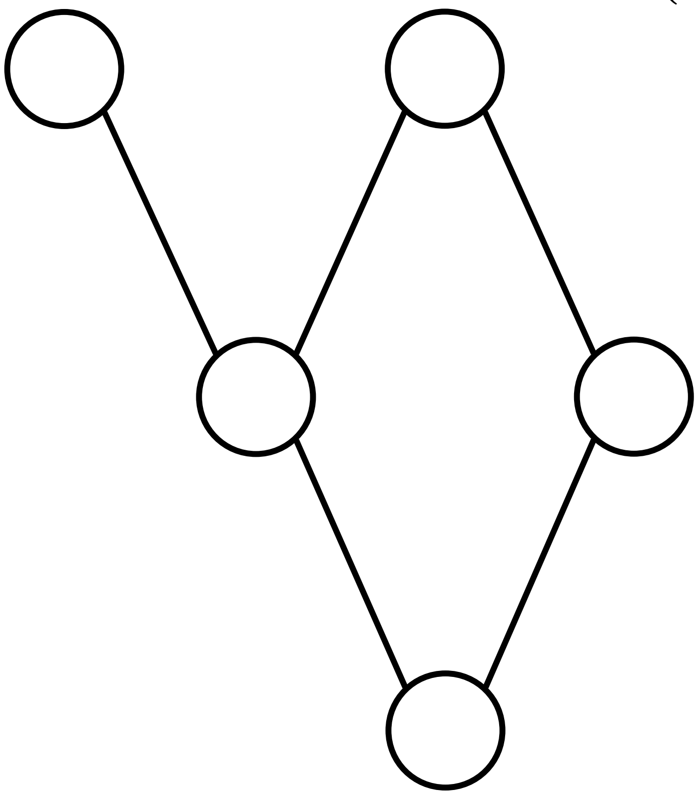


Parametrizing Edges Iteratively

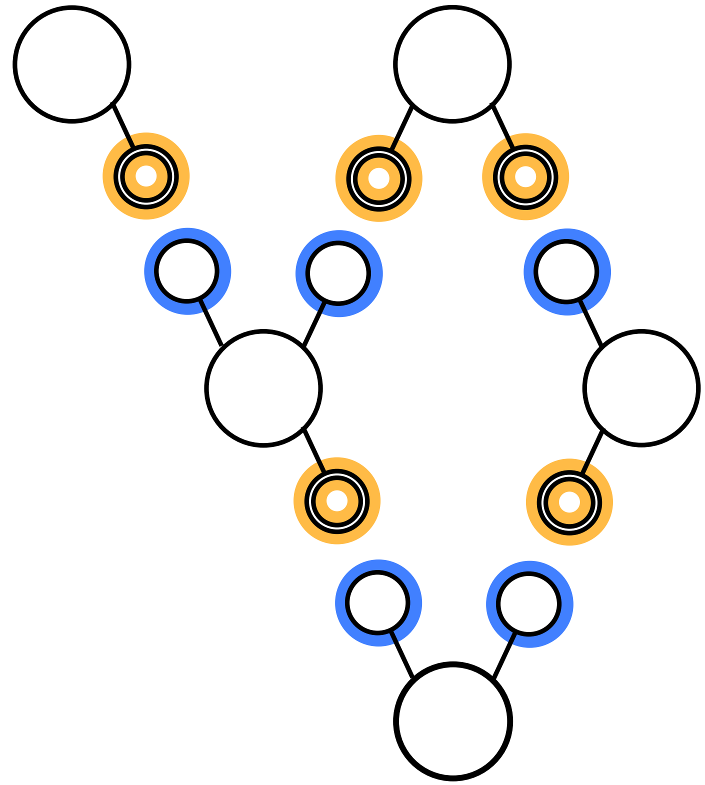


Parametrizing Edges Iteratively

$$\theta(X_i) = \alpha \frac{\partial Z}{\partial \theta(X_j)}$$



$$\theta(X_j) = \alpha \frac{\partial Z}{\partial \theta(X_i)}$$

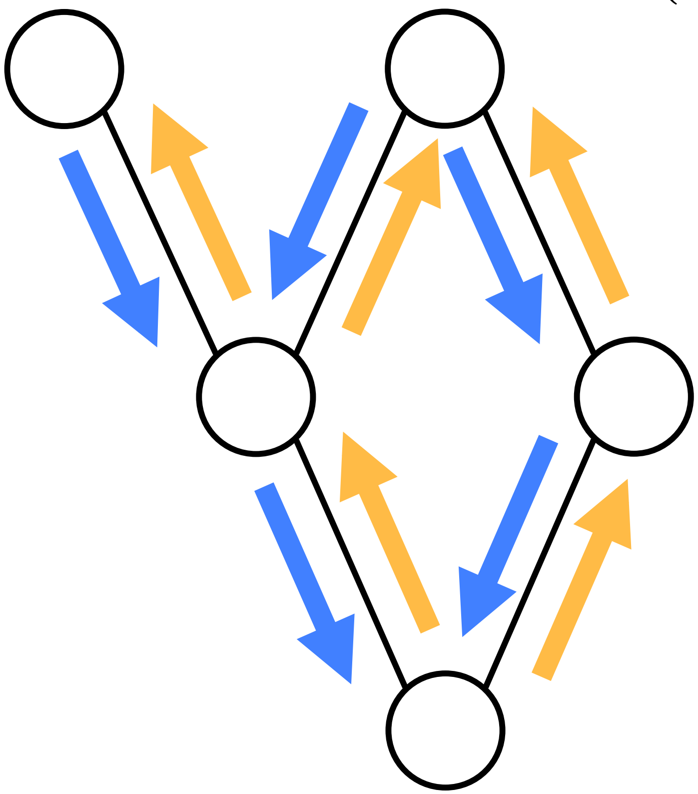


Iteration t

Convergence

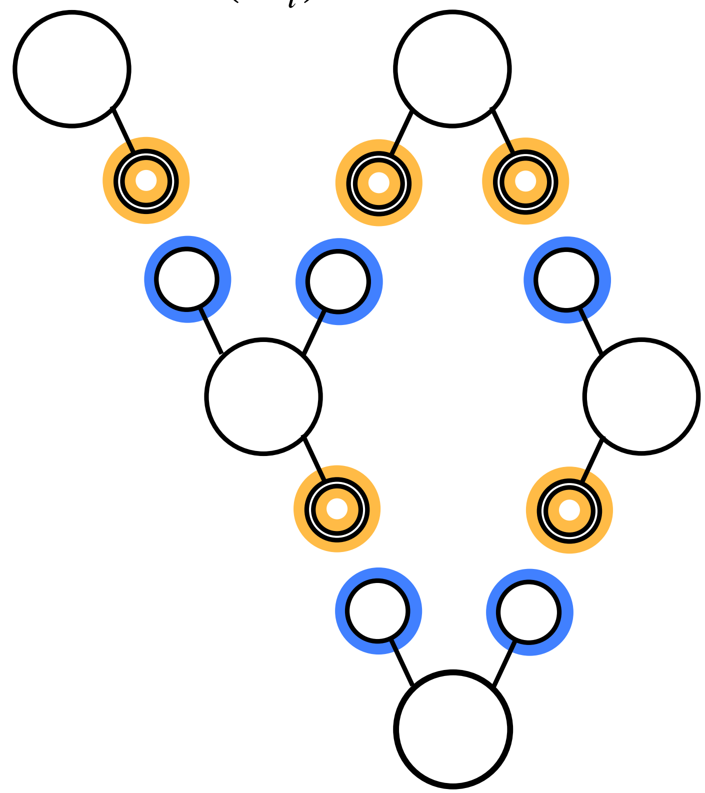
Characterizing Loopy Belief Propagation

$$\theta(X_i) = \alpha \frac{\partial Z}{\partial \theta(X_j)}$$



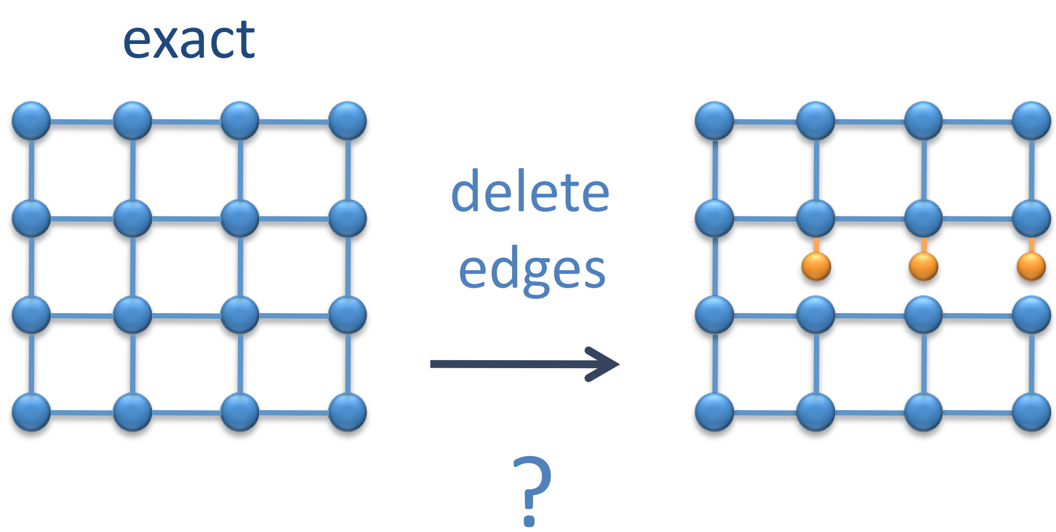
Iteration t

$$\theta(X_j) = \alpha \frac{\partial Z}{\partial \theta(X_i)}$$

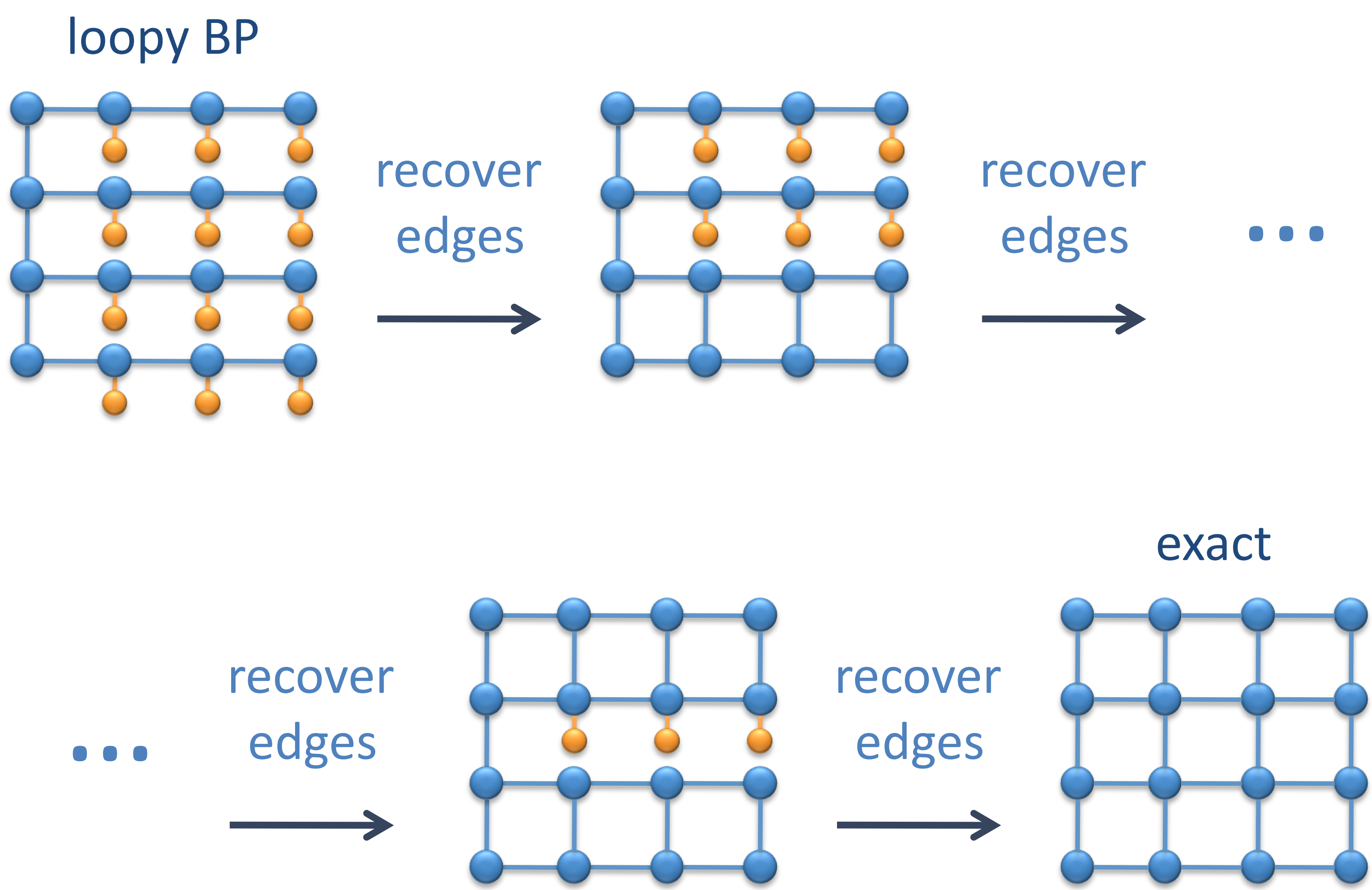


Iteration t

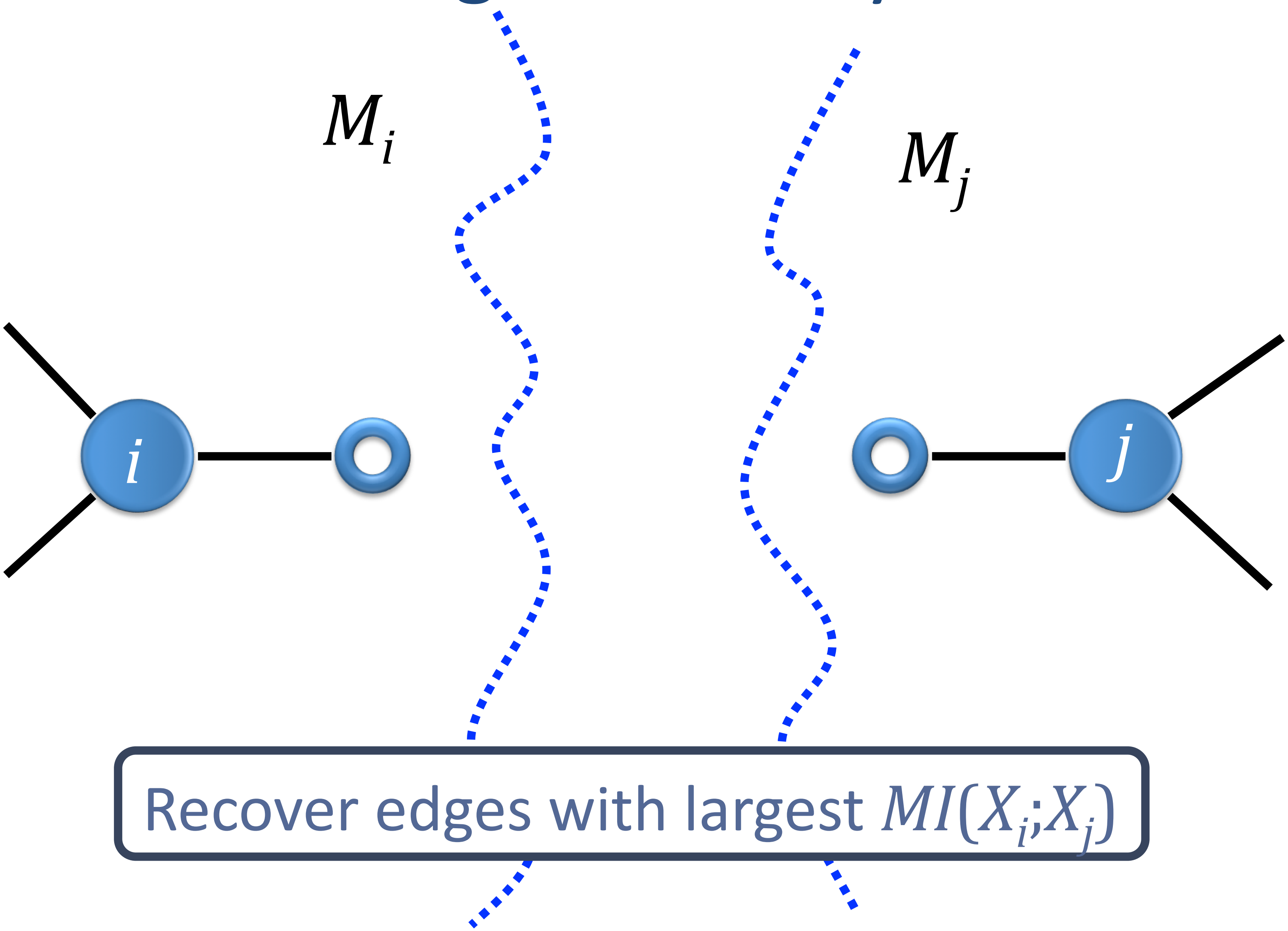
Which Edges to Delete?



Edge Recovery

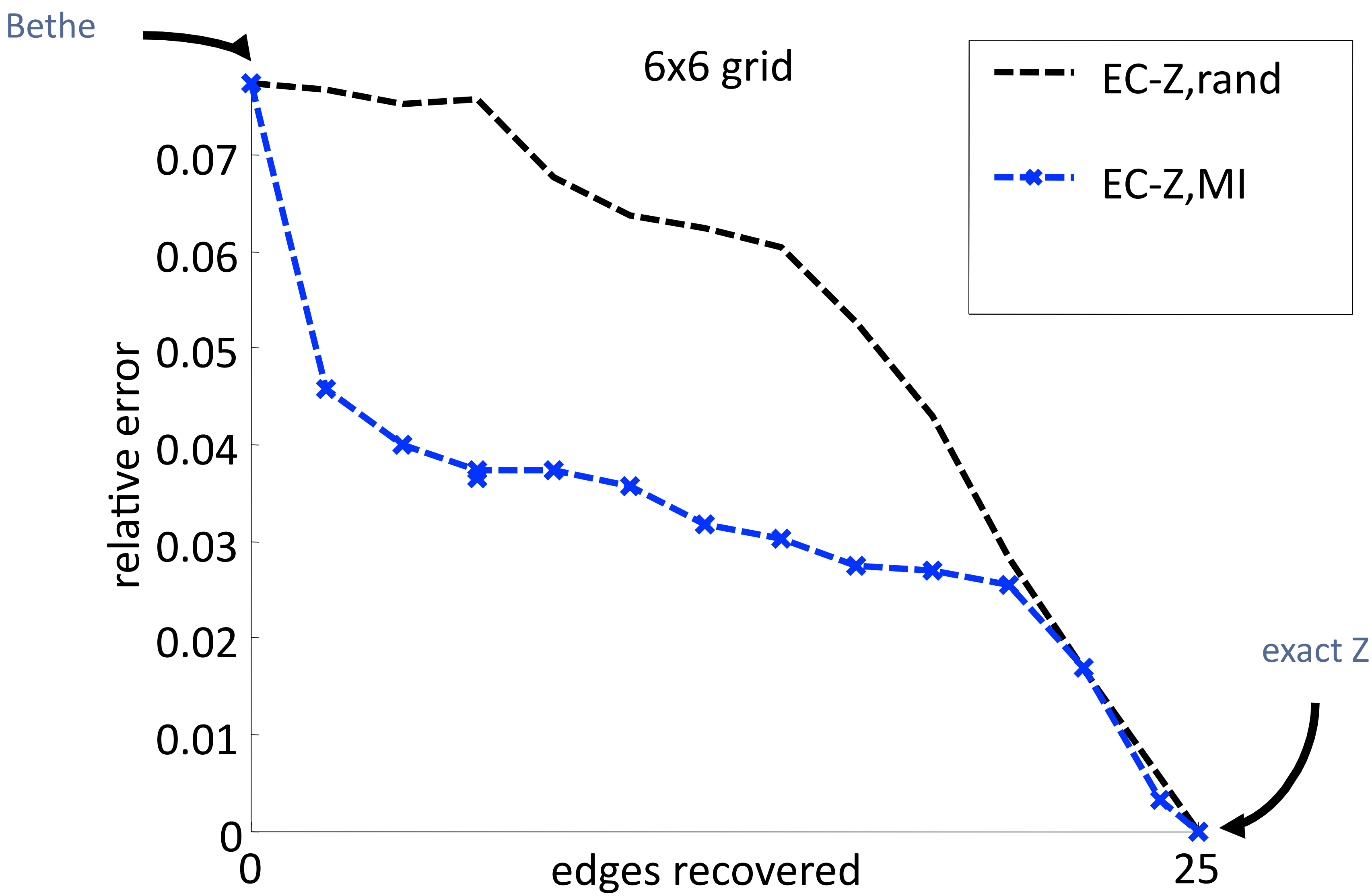


Edge Recovery



Recover edges with largest $MI(X_i;X_j)$

Edge Recovery



Evaluation Benchmarks

Benchmark	PR	MAR	MPE
CSP	8	8	55
Grids	20	20	40
Image Alignment			10
Medical Diagnosis	26	26	
Object Detection	96	96	92
Pedigree	4	4	
Protein Folding			21
Protein-Protein Interaction			8
Segmentation	50	50	50
TOTAL	204	204	287

Overall Results

PR Task: 20 Seconds

Solver	Score
edbr	1.7146
vgogate	2.1620
libDai	2.2775

MAR Task: 20 Seconds

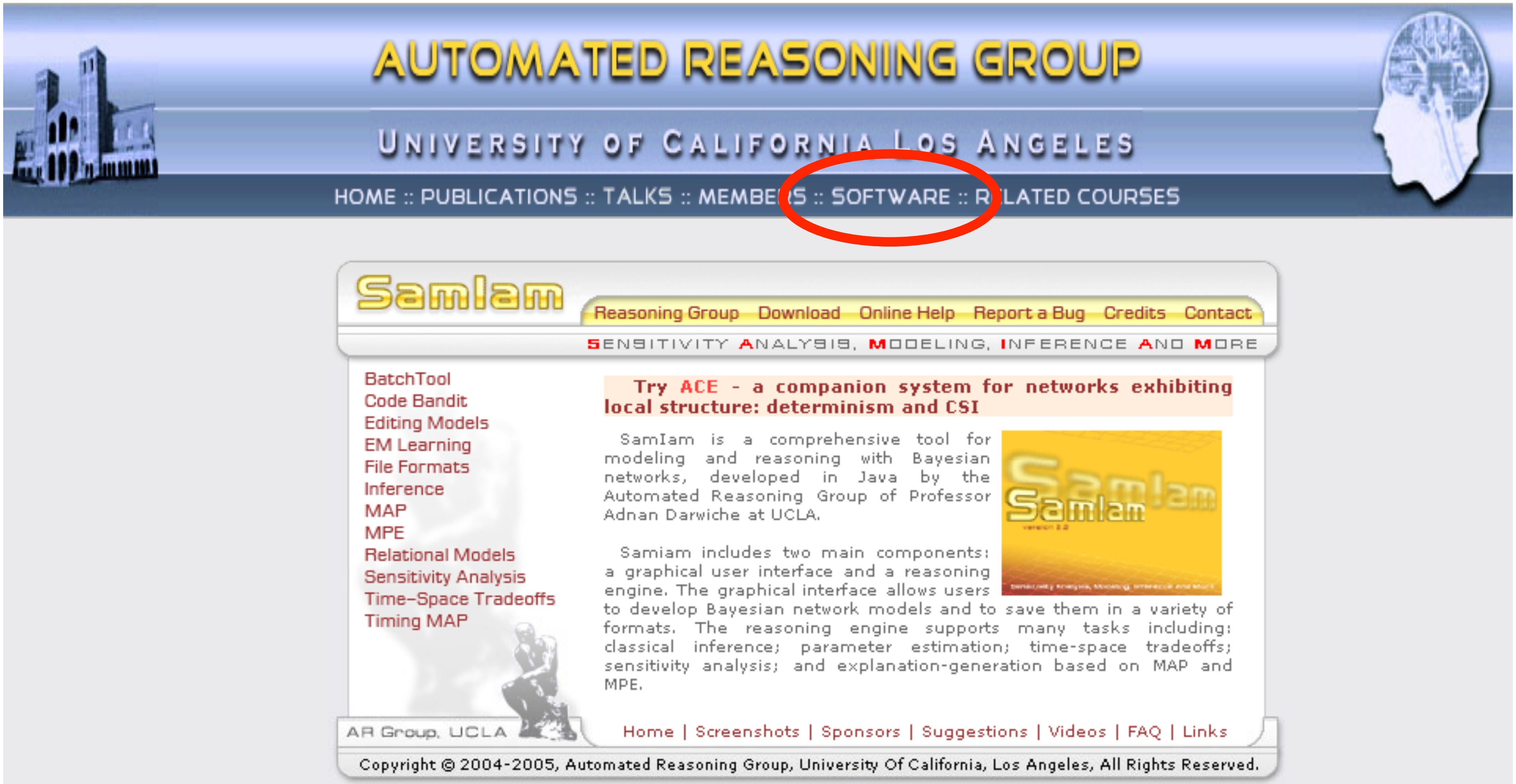
Solver	Score
edbq	0.2390
libDai2	0.3064
vgogate	0.4409

Ideally…

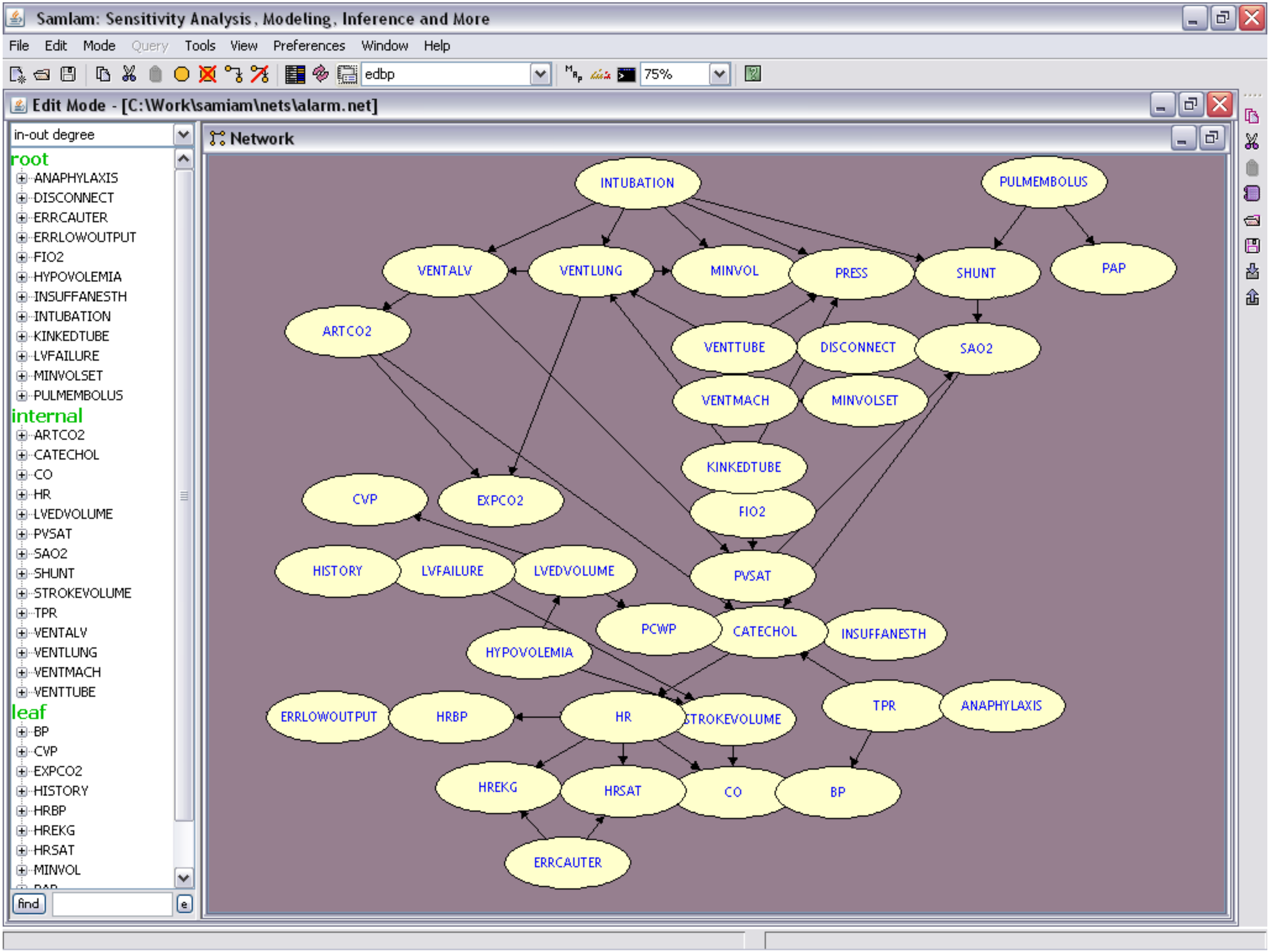
- Exact inference based on compiling CNFs
- Edge recovery using incremental compilation:
  - conjoin recovered equivalence constraint with current compilation
- Not there yet: more engineering needed!

Key Ideas

- **Approximate inference:** formulated as exact inference in an approximate model
- **Approximate models**: obtained by relaxing and compensating for equivalence constraints
- **Anytime inference:** selective recovery of equivalence constraints
- **Exact inference:** formulated in terms of enforcing decomposability and determinism of propositional knowledge bases



http://reasoning.cs.ucla.edu/samiam/


Samlam: Sensitivity Analysis, Modeling, Inference and More
File Edit Mode Query Tools View Preferences Window Help
edbp
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ERRCAUTER
ERRLOWOUTPUT
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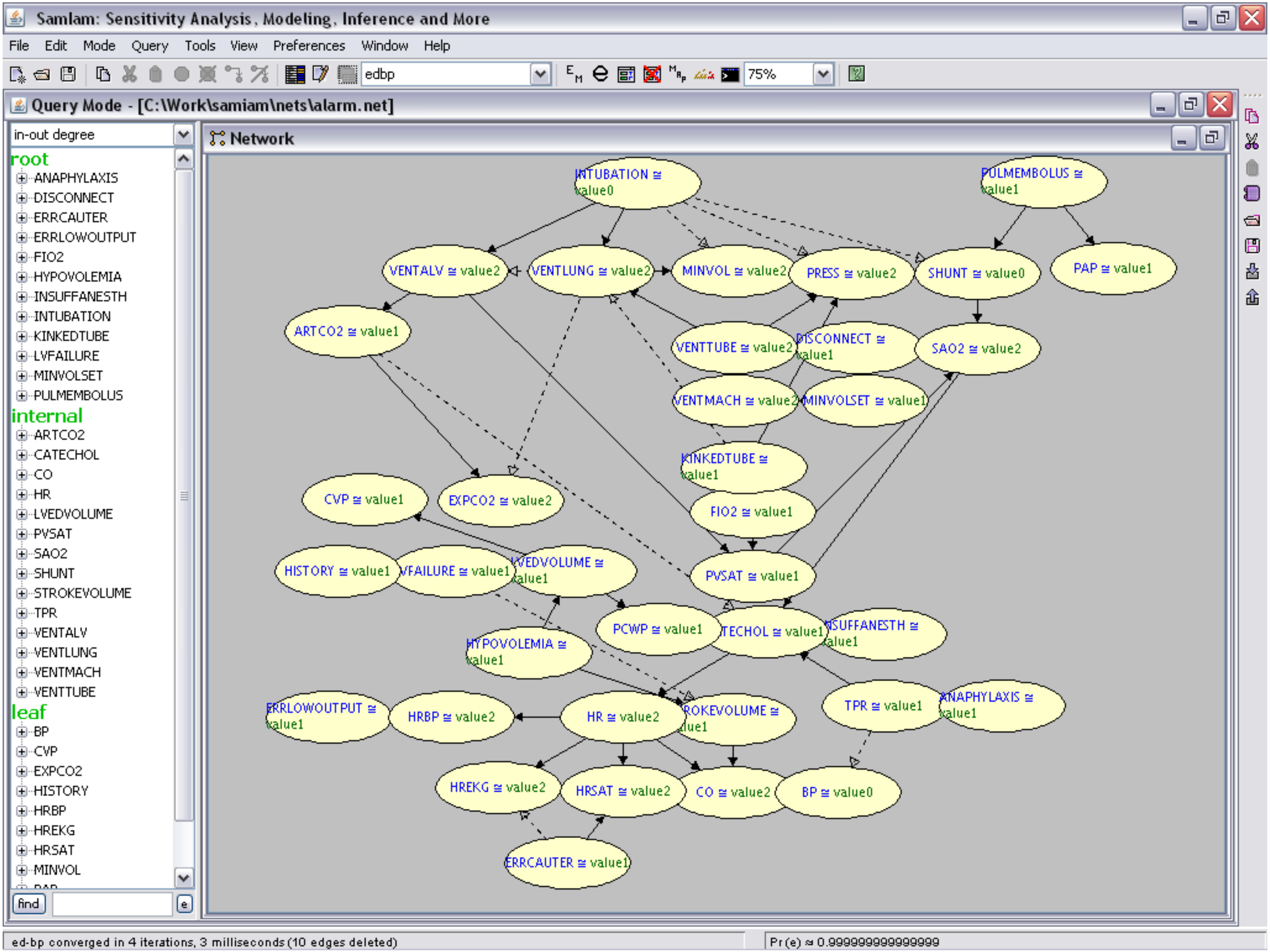
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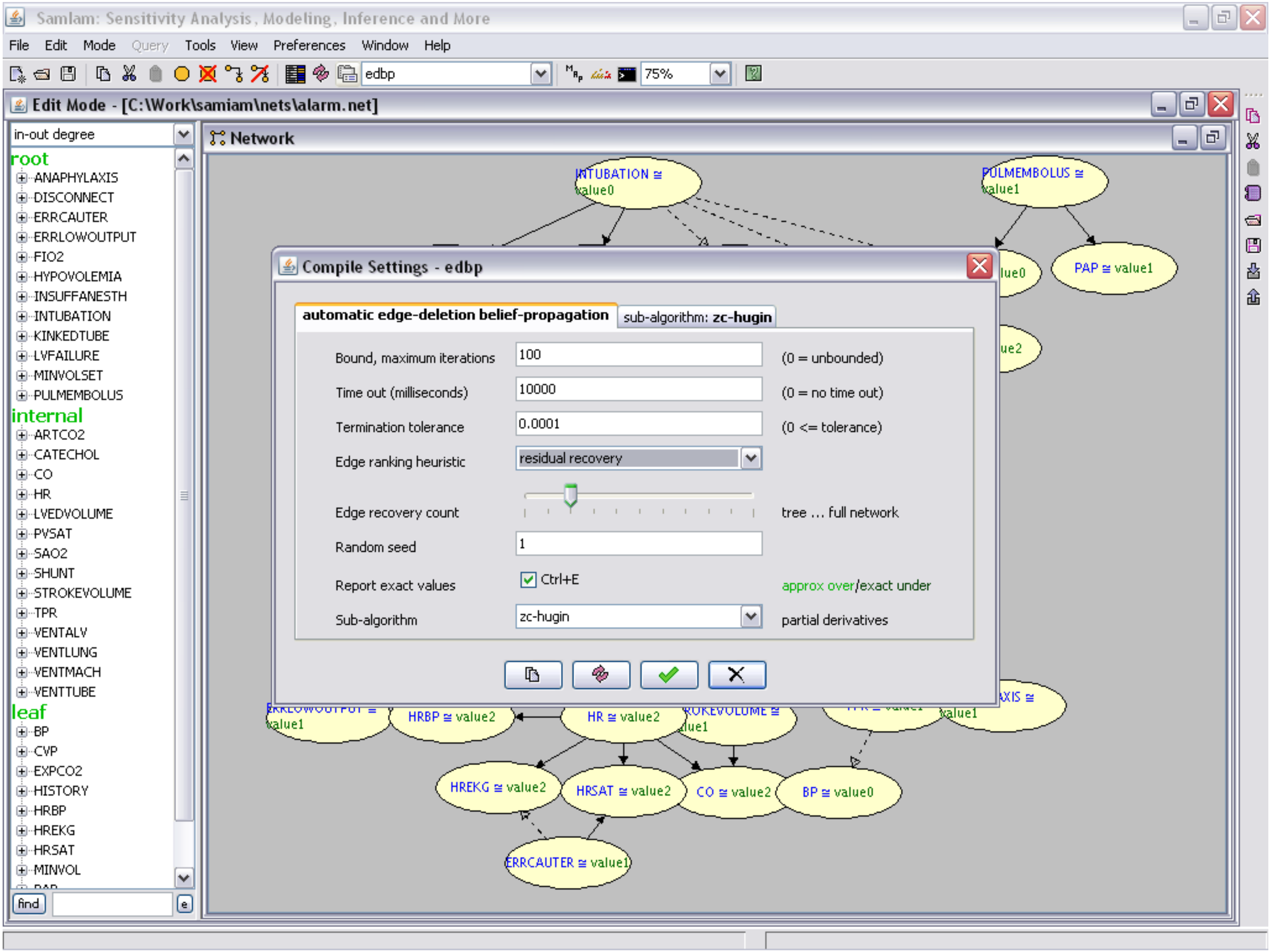
HREKG ≅ value2
HRSAT ≅ value2
CO ≅ value2
BP ≅ value0
ERRCAUTER ≅ value1
ed-bp converged in 4 iterations, 3 milliseconds (10 edges deleted)
Pr(e) ≈ 0.999999999999999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HRSAT ≅ value2
CO ≅ value2
BP ≅ value0
ERRCAUTER ≅ value1
Compile Settings - edbp
automatic edge-deletion belief-propagation
sub-algorithm: zc-hugin
Bound, maximum iterations
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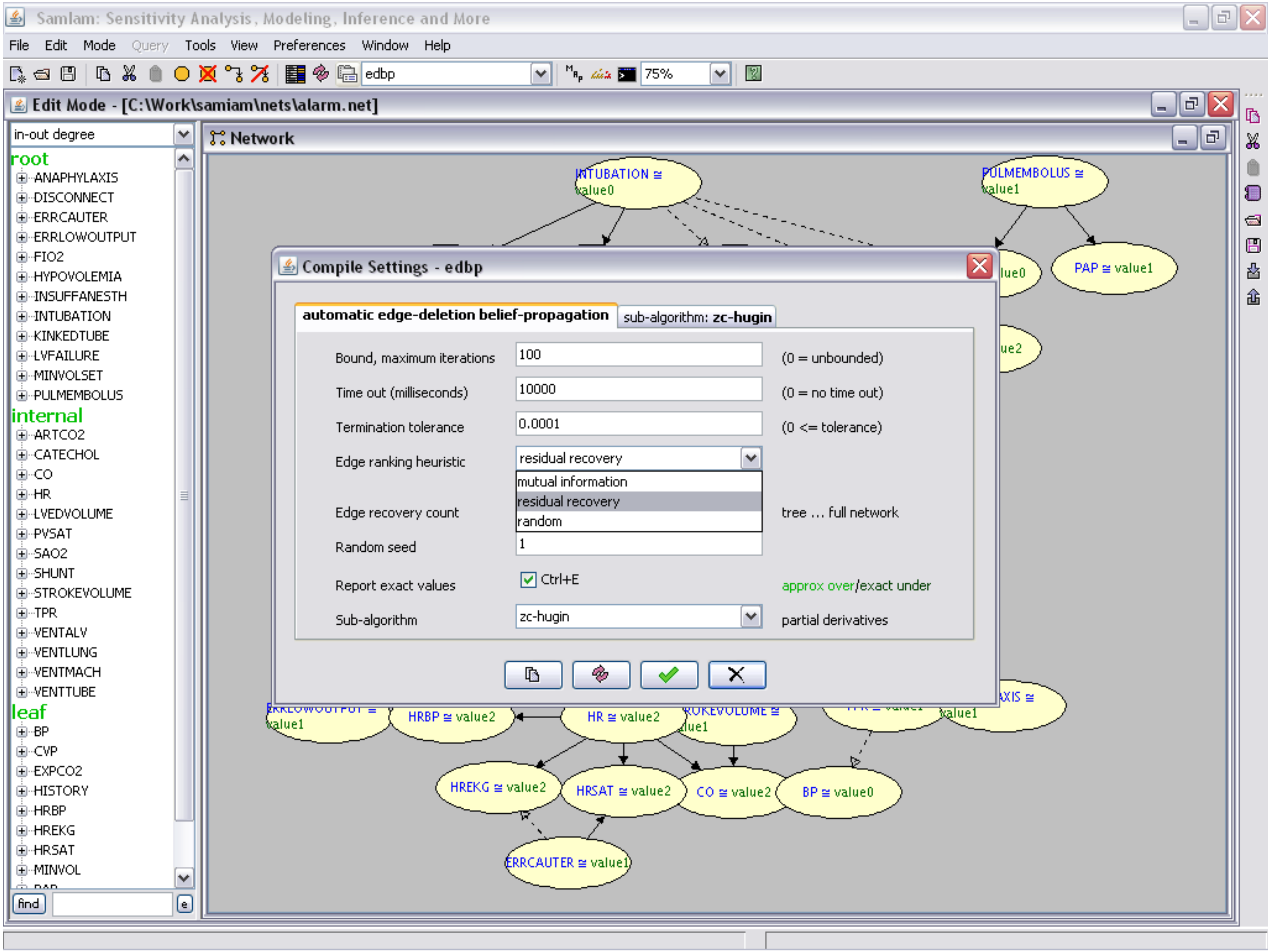
(0 = unbounded)
Time out (milliseconds)
10000
(0 = no time out)
Termination tolerance
0.0001
(0 <= tolerance)
Edge ranking heuristic
residual recovery
Edge recovery count
tree … full network
Random seed
1
Report exact values
Ctrl+E
approx over/exact under
Sub-algorithm
zc-hugin
partial derivatives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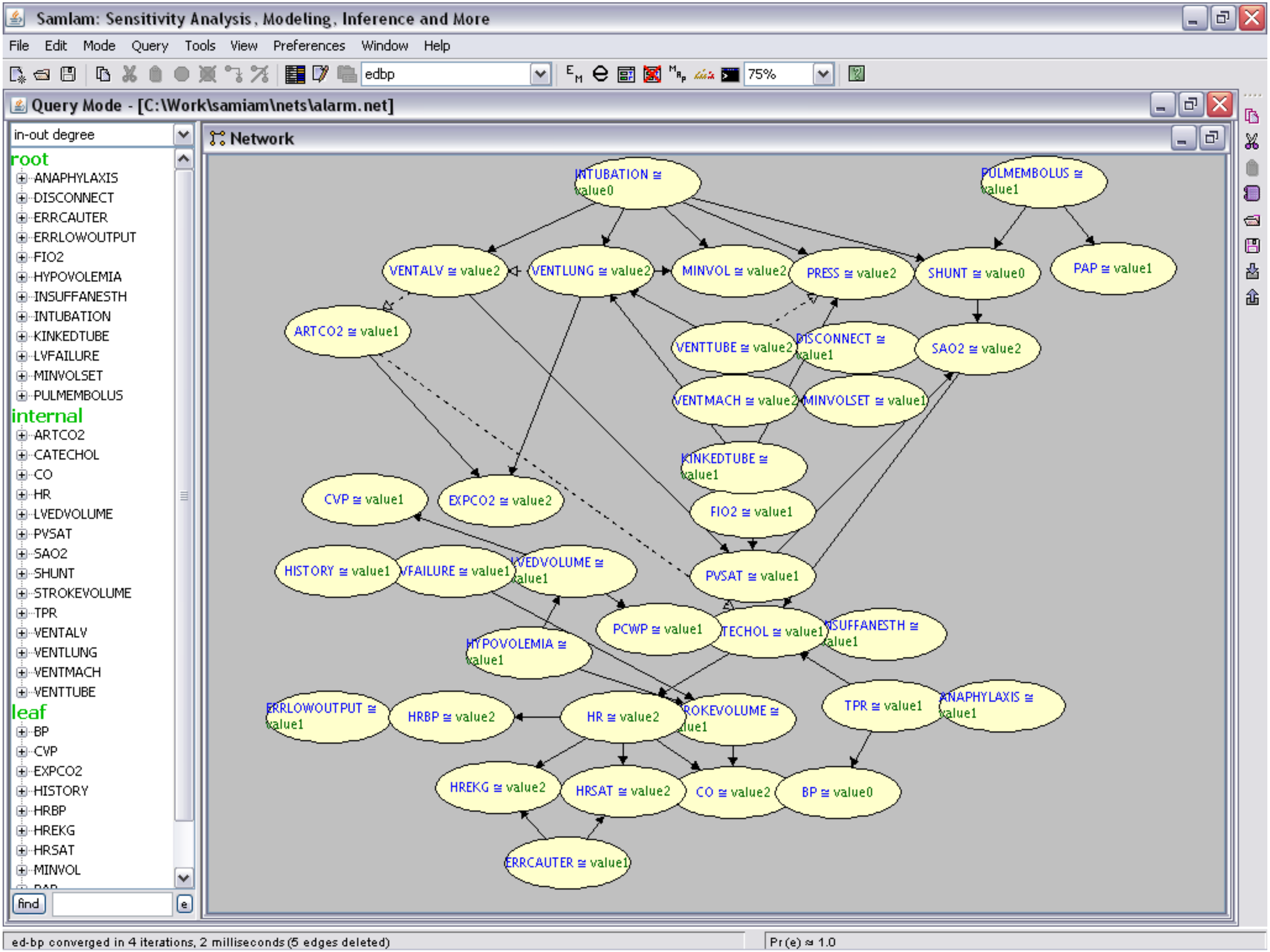
HRBP ≅ value2
HR ≅ value2
HREKG ≅ value2
HRSAT ≅ value2
CO ≅ value2
BP ≅ value0
ERRCAUTER ≅ value1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HRSAT ≅ value2
CO ≅ value2
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ERRCAUTER ≅ value1
ed-bp converged in 4 iterations, 2 milliseconds (5 edges deleted)
Pr(e) ≈ 1.0

Adnan Darwiche

MODELING AND REASONING with BAYESIAN NETWORKS

CAMBRIDGE

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