Compilability and Space Efficiency in Knowledge Representation

a retrospective

in ricordo di Marco Cadoli

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Outline of this talk

1. History and motivations
   (a) Compilation in early ’90s—from my viewpoint
   (b) NMR in early ’90s—again, from my viewpoint
2. Non-uniform Complexity Classes
3. First results: compactness vs. complexity
4. New motivations: Space efficiency
5. Compilability classes
6. Compilation goes on...—an incomplete list

History and Motivations

Knowledge Compilation

- In early 90's, several researchers used the word "compilation" to mean a *pre-processing* step — intended to speed-up *reasoning*
  - information used in reasoning tasks does not come all at once
- term "Knowledge Compilation" used by [Anderson, 1983] about psychological learning experiments

Compiling KB into a Horn KB

[Kautz and Selman, 1991a] $\Rightarrow$[1996]

- Propositional Knowledge Base KB
  - deciding $KB \models \varphi$ is co$\mathcal{NP}$
  - if KB_h is Horn, $KB_h \models \varphi$ is in $\mathcal{P}$
- idea: *compile* KB into an approximation KB_h
- works if *size* $||KB_h||$ is "small" wrt$||KB||$
- "small" $\approx$ poly-size

Size of Horn compilations

- Is there an algorithm $\mathcal{A}$ that
  - given KB
  - outputs KB_h approximating KB
- such that $||KB_h|| \leq \text{poly}(||KB||)$ *?*
- even a nonrecursive $\mathcal{A}$ does not exists, unless $\Sigma_2^p = \Pi_2^p$ [Kautz and Selman, 1992]

Compiling KB into its models

[Khardon and Roth, 1994] $\Rightarrow$[1996]

- compile propositional KB into an efficient representation of its models
- use models to answer queries:
  - $KB \models \varphi$ iff there is no model falsifying φ

In the meanwhile . . .

Non-Monotonic Reasoning

- Circumscription [McCarthy, 1980]
- Default Logic [Reiter, 1980]
- Closed World Assumption [Minker, 1982]
- Autoepistemic Logic [Moore, 1985]
- Well-Founded Semantics for LP
  [van Gelder *et al.*, 1991]
- . . .

How many of you know. . . — Can I skip this slide?

Circumscription of Knowledge Base KB

- model of KB = set of atoms M (true atoms)
- *minimal* M = no subset of M is a model of KB
- models of $CIRC(KB)$ = *minimal models* of KB
- $Models(a \vee b) = \{\{a\}, \{b\}, \{a, b\}\}$
- $Models(CIRC(a \vee b)) = \{\{a\}, \{b\}, \{\not a, \not b\}\}$

Why NMR?

(from Marco's PhD thesis [Cadoli, 1995])

In case of fire
do NOT use the elevator

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In case of fire
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- How one derives that there is no fire?
- $KB = \{fire \equiv (smoke \vee alarm \vee \cdots)\}$
- $CIRC(KB) \models \neg fire$

Why NMR? – 2

[McCarthy, 1980]

> "Circumscription is a rule of conjecture that can be used by a person or program for 'jumping to certain conclusions' "

[Reiter, 1980]

> "...default reasoning...corresponds to...patterns of inference of the form 'in the absence of any information to the contrary, assume...' ."

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- undecidable problems $\Rightarrow$"more" undecidable
  - r.e.-complete $\Rightarrow\Pi_2^p$-complete [Schlipf, 1987]

So, why NMR?

[Brachman, 1990]:

> "An irony of work on NMR is that, while the easy adoption and retraction of assumptions is most useful for speeding up natural everyday reasoning, most current NMR proposals drastically compound the already difficult problem of deductive reasoning. We urgently need to determine how NMR can be used to make commonsense inference faster, not slower."

Intuition about NMR

[Cadoli *et al.*, 1994] $\Rightarrow$[1996b]

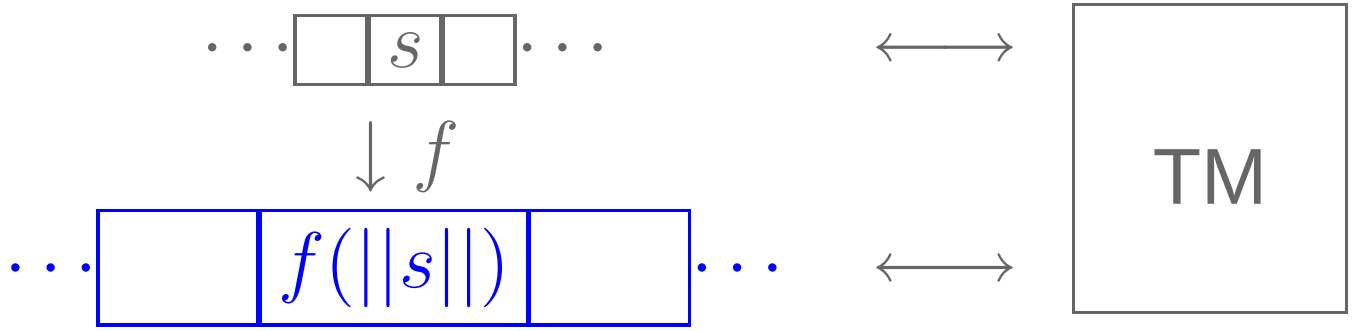
- "Is intractability of non-monotonic reasoning a real drawback?"
- No: complexity of NMR is balanced by savings in *space* when representing knowledge
- (. . . How to prove this claim?)

Techniques:
Non-uniform complexity classes

Advice-taking Turing machines

cfr. [Johnson, 1990]

- two tapes: normal tape, advice tape
- function f (not necessarily recursive)
- on input s, load advice tape with $f(||s||)$
- computation proceeds as normal, based on both s and $f(||s||)$



Polynomial advice

An advice-taking Turing machine uses *polynomial advice* if . . .

- condition on the advice oracle f:
- $\exists$poly s.t. $||f(n)|| \leq \text{poly}(n)$ for all $n = 1, 2, 3, \ldots$
- *one* polynomial (always the same)

Non-uniform polynomial hierarchy

- $\mathcal{C} \in \{\mathcal{P}, \mathcal{NP}, co\mathcal{NP}, \Sigma_2^p, \Pi_2^p, \ldots\}$ (polynomial hierarchy)
- $\mathcal{C}$/poly = $\mathcal{C}$ augmented by polynomial advice
  - e.g. $\mathcal{NP}$/poly = $\mathcal{NP}$ + a poly guess based on the *size* of the input
- *Non-uniform* polynomial hierarchy:
  - $\mathcal{P}$/poly, $\mathcal{NP}$/poly, Σ_2^p/poly, ...

Complexity results

- if $\mathcal{NP} \subseteq \mathcal{P}/\text{poly}$ then $\Sigma_2^p = \Pi_2^p$ [Karp and Lipton, 1980]
- if $\Sigma_n^p \subseteq \Pi_n^p/\text{poly}$ then $\Sigma_{n+2}^p = \Pi_{n+2}^p$ [Yap, 1983]
- Conclusion:
  - one cannot use polynomial advice to *compile* time complexity unless . . .
  - . . . the polynomial hierarchy *collapses* at some level

First Results

Compilation

- generalization of knowledge compilation
- [Cadoli *et al.*, 1994] "We call *compilation* any off-line process that makes on-line reasoning polynomial"
- More generally, compilation should *decrease* complexity
  - e.g. from Π_2^p to co$\mathcal{NP}$
  - a *lower* class in the polynomial hierarchy

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- $CIRC()$ *compacts* knowledge

Compiling CIRC – 2

[Cadoli *et al.*, 1995b] $\Rightarrow$[1997]

- KB a propositional formula
  - $KB \models \varphi$ is in co$\mathcal{NP}$
  - $CIRC(KB) \models \varphi$ is Π_2^p-complete [Eiter and Gottlob, 1993]
- $CIRC(KB)$ could be compiled to a *formula* iff $\mathcal{NP} \subseteq \mathcal{NC}^1/\text{poly}$
- $CIRC(KB)$ could be compiled to a *data structure* iff $\mathcal{NP} \subseteq \mathcal{P}/\text{poly}$

Compiling Belief Revision

- P new knowledge
- $KB \wedge P \models \bot$ (incosistent)
- $KB * P$ = KB *revised* with P
- Express $KB * P$ as an equivalent formula KB'
- does always exist KB' poly-size wrt KB, P *?*

Compiling Belief Revision

[Cadoli *et al.*, 1995a] $\Rightarrow$[1999]

Revision defined by...	General P		Bounded P	
	Same atoms	New Atoms	Same atoms	New Atoms
GFUV, Nebel	NO	NO	NO	NO
Winslett	NO	NO	YES	YES
Borgida	NO	NO	YES	YES
Forbus	NO	NO	YES	YES
Satoh	NO	NO	YES	YES
Dalal	NO	YES	YES	YES
Weber	NO	YES	YES	YES
WIDTIO	YES	YES	YES	YES

GFUV = Ginsberg — Fagin, Ullman, Vardi

WIDTIO = “When in doubt, throw it out”

New Motivations: Space Efficiency of KR formalisms

Representing knowledge

- **Assumption:** KB in a formalism F represents either:
  - the set of *models* of KB in F, or
  - the set of *theorems* derivable from KB in F
- Compare succintness of propositional KR formalisms

Comparing KR formalisms

Same "piece of knowledge" can be expressed as:

- KB_1 in formalism F_1
- KB_2 in formalism F_2
- *Relative* space efficiency:
  - compare $||KB_1||$ and $||KB_2||$

Translating knowledge

formalism F_1	shortest translation f (even an oracle)	formalism F_2
KB_1^1	$\mapsto$	KB_2^1
KB_1^2	$\mapsto$	KB_2^2
$\vdots$	$\vdots$	$\vdots$

- if $||KB_2^i||$ grows exponentially wrt $||KB_1^i||$,
- and not vice versa, then
- F_1 is relatively more space efficient than F_2

Poly-size reductions among formalisms

$$f : F_1 \mapsto F_2$$

- the result of $f(KB)$ is poly-size wrt $||KB||$
- for any given KB in F_1, $f(KB)$ is a knowledge base in F_2

Reductions preserving models

- f preserves models if

$$\forall KB: \ \exists g: \ \forall M: \left[\begin{array}{ccc} M & \models_{F_1} & KB \\ g\downarrow & & \downarrow f \\ g(M) & \models_{F_2} & f(KB) \end{array}\right]$$

- where g is poly-time ("easy to compute")
- Note: g depends on KB

Example

[Etherington, 1987]

PFN-Skeptical Default Logic $\mapsto$ Circumscription

$$\left[\begin{array}{ccc} & \exists\text{extension} & \\ M & \models_{SK} & \langle\{\frac{:\gamma_i}{\gamma_i}\}, W\rangle \\ g \downarrow & & \downarrow f \\ M \cup \{a_i | M \models \gamma_i\} & \models_{CIRC} & W \cup \{a_i \equiv \neg\gamma_i\} \\ & \text{minimizes } a_i & \end{array}\right.$$

Reductions preserving theorems

- f preserves theorems if

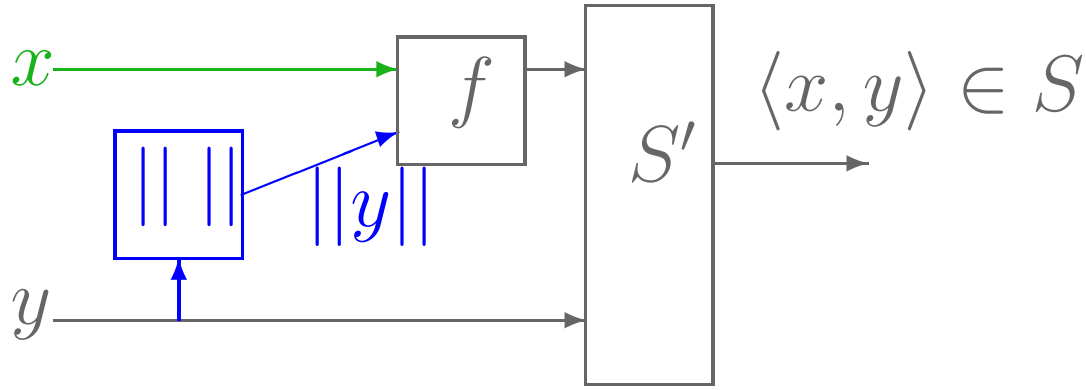
$$\forall KB: \ \exists g: \ \forall Q: \begin{bmatrix} KB & \vdash_{F_1} & Q \\ f \downarrow & & \downarrow g \\ f(KB) & \vdash_{F_2} & g(Q) \end{bmatrix}$$

- where g is poly-time and $||Q|| \leq ||KB||$
- Note: g depends on KB

Generalizing Techniques

NU-Compilability

[Cadoli *et al.*, 1996a] $\Rightarrow$[2002]
Non-Uniform compilability

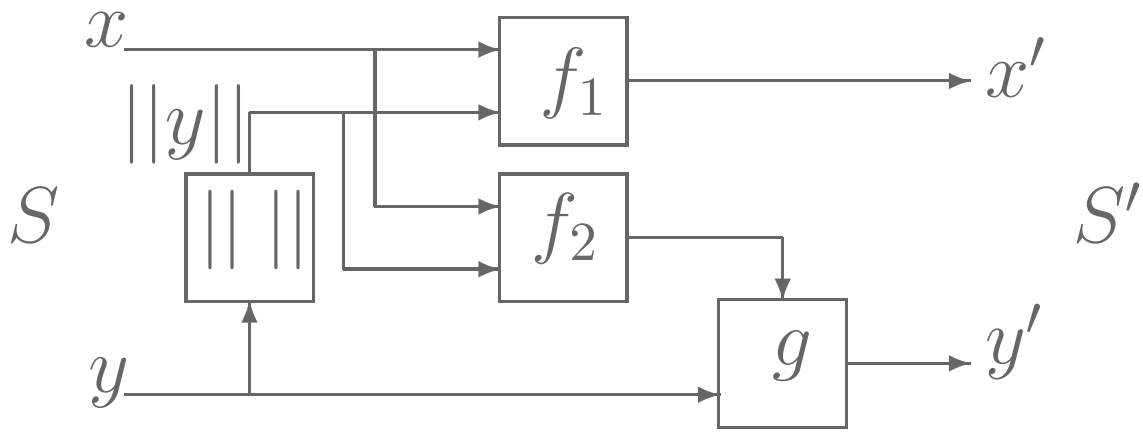


Combines:

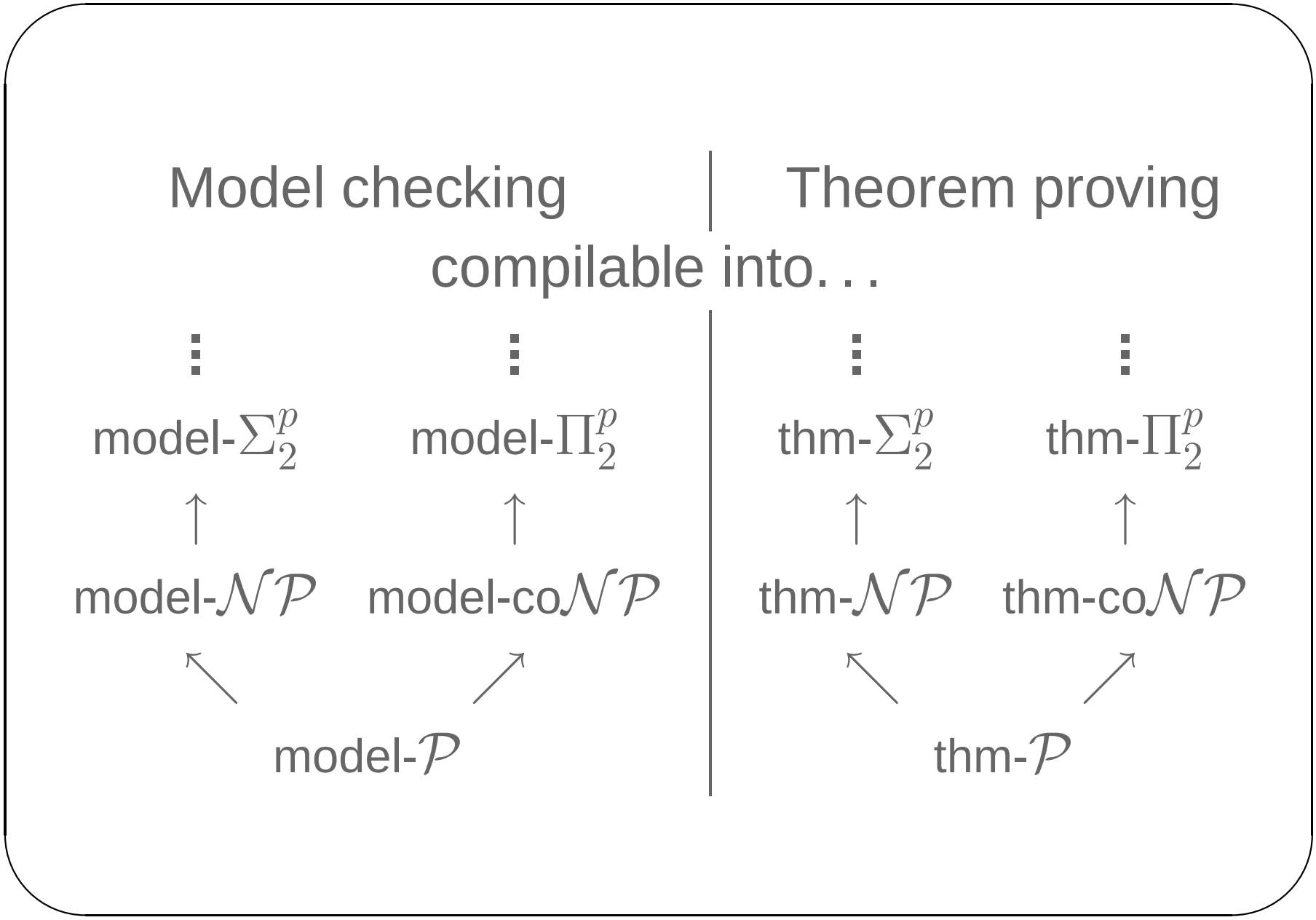
- the $\mathcal{P}$/poly machine (size of y)
- the compilability machine (fixed part x)
- compilability implies nu-compilability

Reductions

- Suppose problem $S = \{\langle x, y \rangle\}$ can be reduced to problem $S' = \{\langle x', y' \rangle\}$
- if S is non-compilable, so is S'



Compilability Classes



Space Efficiency of KR formalisms

	Time Complexity		*Space Efficiency*	
	Models	Theorems	Models	Theorems
Propositional Logic	$\mathcal{P}$	co$\mathcal{NP}$ •	model-$\mathcal{P}$	thm-co$\mathcal{NP}$•
WIDTIO Belief Rev.	Σ_2^p•	Π_2^p•	model-$\mathcal{P}$	thm-co$\mathcal{NP}$•
Skeptical Belief Rev.	co$\mathcal{NP}$ •	Π_2^p•	model-co$\mathcal{NP}$•	thm-Π_2^p•
Circumscription	co$\mathcal{NP}$ •	Π_2^p•	model-co$\mathcal{NP}$•	thm-Π_2^p•
GCWA	$\Delta_2^p[\log n]\downarrow$ co$\mathcal{NP}$ $\uparrow$	Π_2^p•	model-$\mathcal{P}$	thm-co$\mathcal{NP}$•
Skeptical Default Reas.	Σ_2^p•	Π_2^p•	model-Σ_2^p•	thm-Π_2^p•
Credulous Default Reas.	N/A	Σ_2^p•	N/A	thm-Σ_2^p•
Stable Models in LP	P	co$\mathcal{NP}$ •	model-$\mathcal{P}$	thm-co$\mathcal{NP}$•

• — complete

$\uparrow$ — hard

$\downarrow$ — contained

Early 00's: Compilation goes on...

Database Theory for Compilation

[Cadoli and Mancini, 2002]

- express the data as relations
- express the problem as a second-order logic formula φ
- find syntactic forms of φ such that the problem is compilable

Compiling Propositional KB s

[Darwiche and Marquis, 2002]

- compile KB into NNF
- use NNF representation to answer queries
- best JAIR paper award (2006)

Planning

- [Bäckström, 1995] relates planning formalism considering also the *size* of the shortest translation
- [Nebel, 2000] analyses *compilability* between planning formalisms
- [Liberatore, 2001] PLANSAT+ is not compilable, using general methods

Abduction

[Liberatore and Schaerf, 2007]

- given KB, manifestations M, possible hypotheses H
- find a subset H' of H such that
- $H' \cup KB \models M$
- KB is fixed, so it makes sense to preprocess it
- yet all main problems (existence, relevance, necessitiy...) are not compilable

Circuits

[Cadoli *et al.*, 2006]

- error-correcting circuits
- related to Hamming codes
- the size of k-error-correcting circuits cannot be a polynomial in k
- related to Dalal's Belief Revision

Goodbye, Marco...

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In the notes of this slide,
references can be found.

Slides are available at
http://sisinflab.poliba.it/donini

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