Formal Methods for Interactive Systems

Part 8 — Cognitive Architectures

Antonio Cerone
United Nations University
International Institute for Software Technology
Macau SAR China
email: `antonio@iist.unu.edu`
web: `www.iist.unu.edu`

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- physical/device: Keystroke-level Model (KLM)

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$\Longrightarrow$ aim to some performance analysis

but seldom deals with user observation and perception $\Longrightarrow$ mainly competence models

Error Detection

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Users behave rationally
$\Longrightarrow$ make persistent errors

Rational Behaviour

based on

Rational Behaviour behaviour that is intended to achieve a specific goal

in AI: Knowledge-level System $=$ Agent behaves in Environment

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in contrast with

Computational Behaviour behaviour defined by an algorithm without an explicit goal

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Machine does not formulate the problem space (the goal is not programmed)

Cognitive Architectures

- goal to achieve
- $\Longrightarrow$ represented as a set of goal states
- rational behaviour $\Longrightarrow$ to select appropriate operators to generate new states starting form the initial state
- goal achieved once a goal state is reached

based on problem space theory, developed by Newell and Simon [Newell et a. 91]

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- operation application changes the states of the agent and the environment
- goal completion when the new state is a goal state the agent becomes inactive

Knowledge Role

- goal formulation
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knowledge availability $\Longrightarrow$ recursion:
new space problem invoked with
goal $=$ find needed knowledge

SOAR

Executable Cognitive Architecture developped by Allen Newell, John Laird and Paul Rosembloom in 1983 [Newell et a. 87]

Used by the University of Michigan

http://sitemaker.umich.edu/soar/

PUM

Programmable User Models

Psychologically Constrained Architecture which an interface designer is invited to program to simulate a user performing a range of tasks with a proposed interface

[Young et a. 89]

PUM Philosophy

The interface designer

- must program the PUM respecting the constraints
  $\Longrightarrow$ driven interface design
  $\Longrightarrow$ explicit “user program”

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The interface designer

- must program the PUM respecting the constraints
  $\Longrightarrow$ driven interface design
  $\Longrightarrow$ explicit “user program”
- run the model
  ($\Longrightarrow$ “user program” is executable)
  to make predictions
  $\Longrightarrow$ show source of predictions and strategy options

PUM Purposes

- Outcome:
  predictive evaluation to tell the designer usability of a proposed design before it is actually built

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  predictive evaluation to tell the designer usability of a proposed design before it is actually built
- Benefits for the designer:
  - to draw the designer attention to issues of usability
  - to provide a way of reasoning about usability

PUMA: PUM Applications

Research Project aim to

- Bring the PUM metodology into industrial design
- Using formal methods to effectively implement PUM

PUMA Research Group Website:

http://www.cs.mdx.ac.uk/puma/

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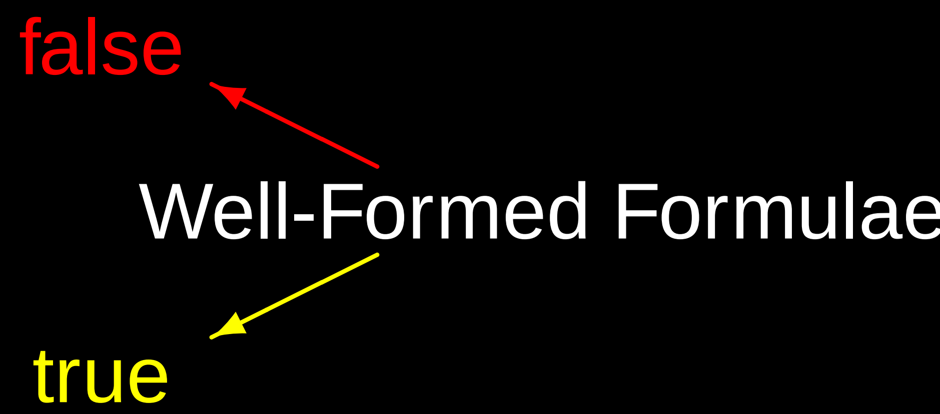
- Automated Correctness Proof
- Informal reasoning to detect errors

Theorem-proving

Well-Formed Formulae

Theorem-proving



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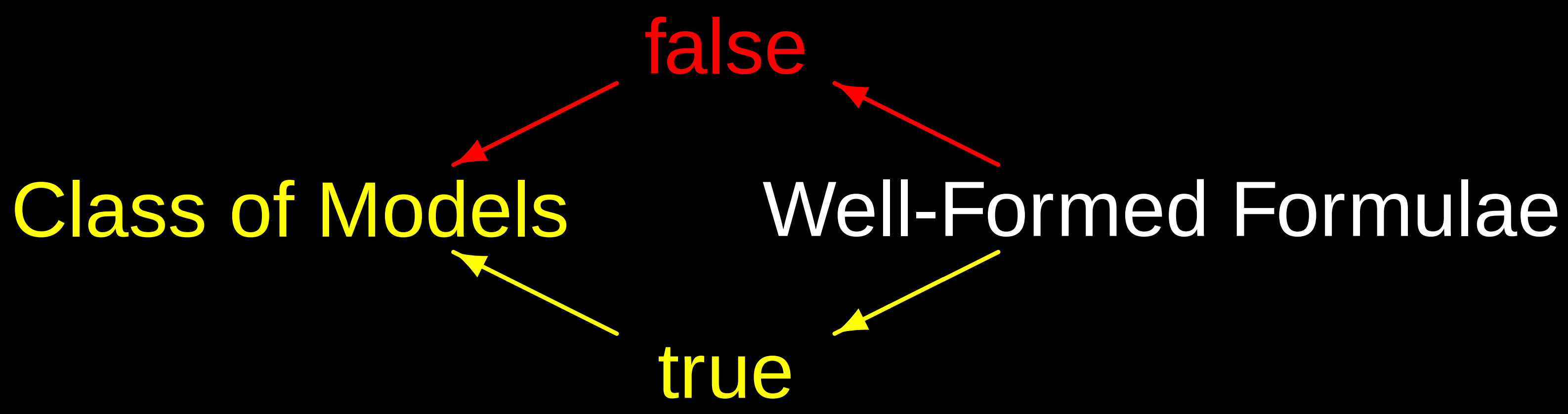

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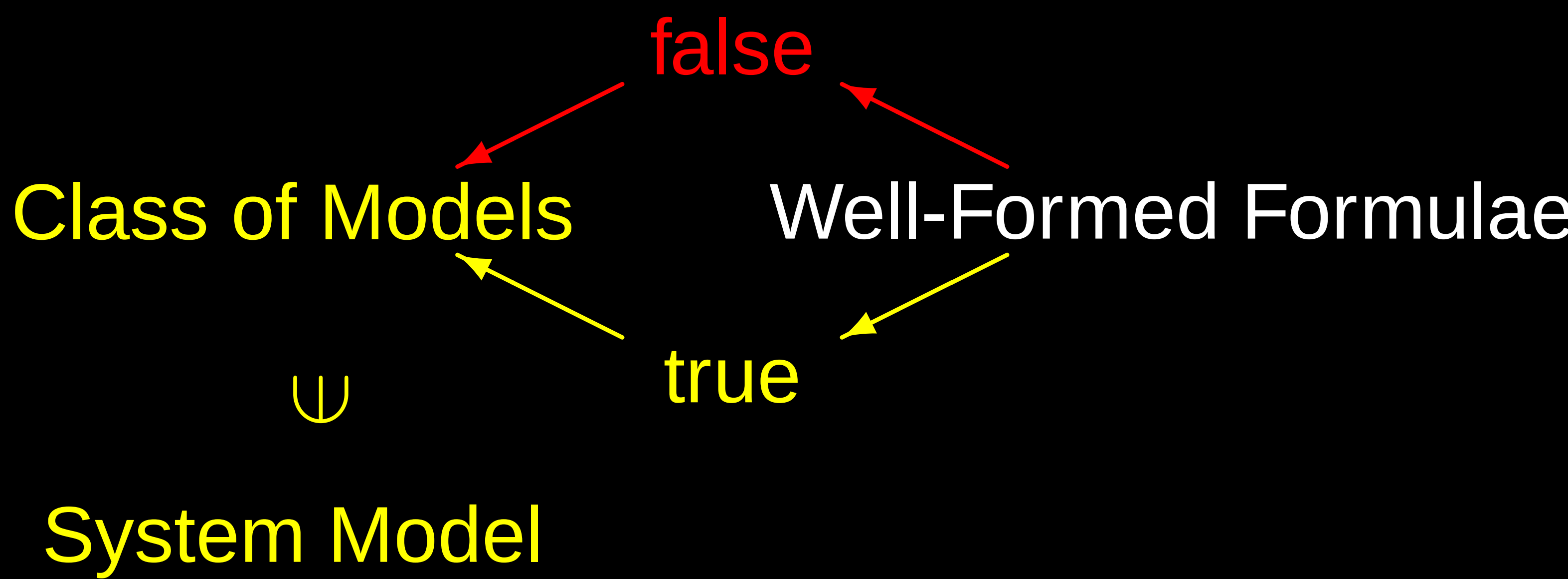

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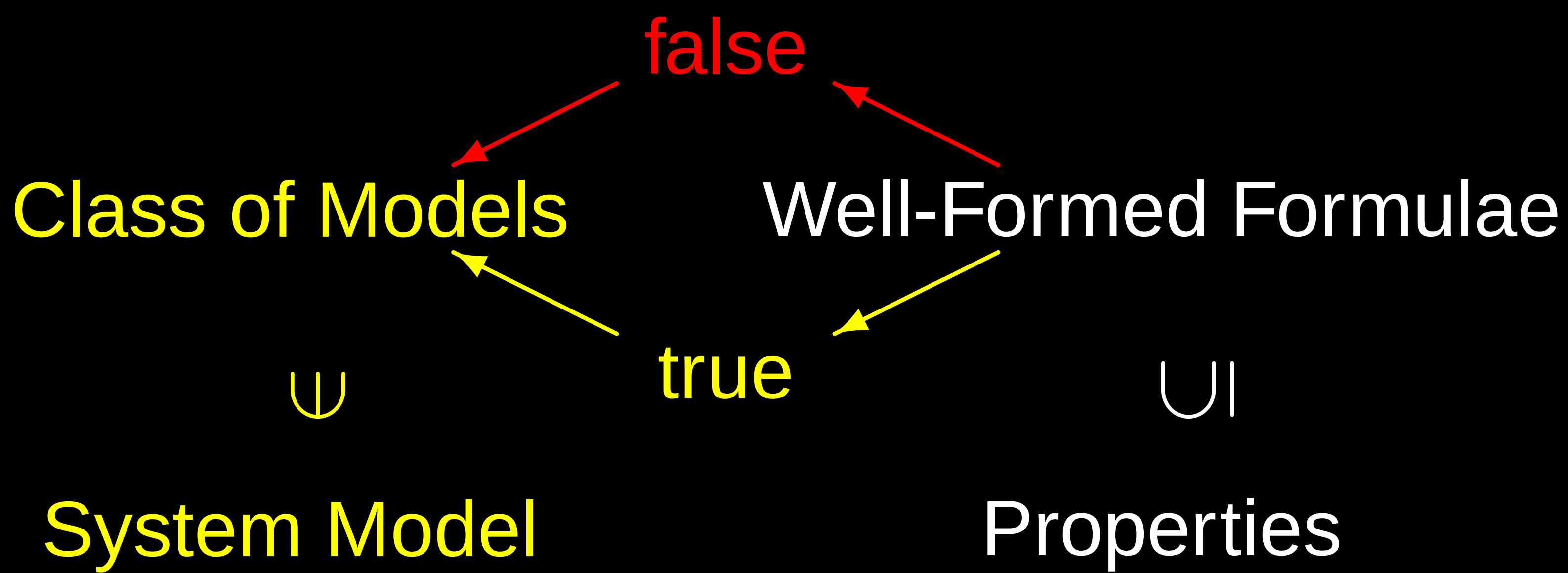

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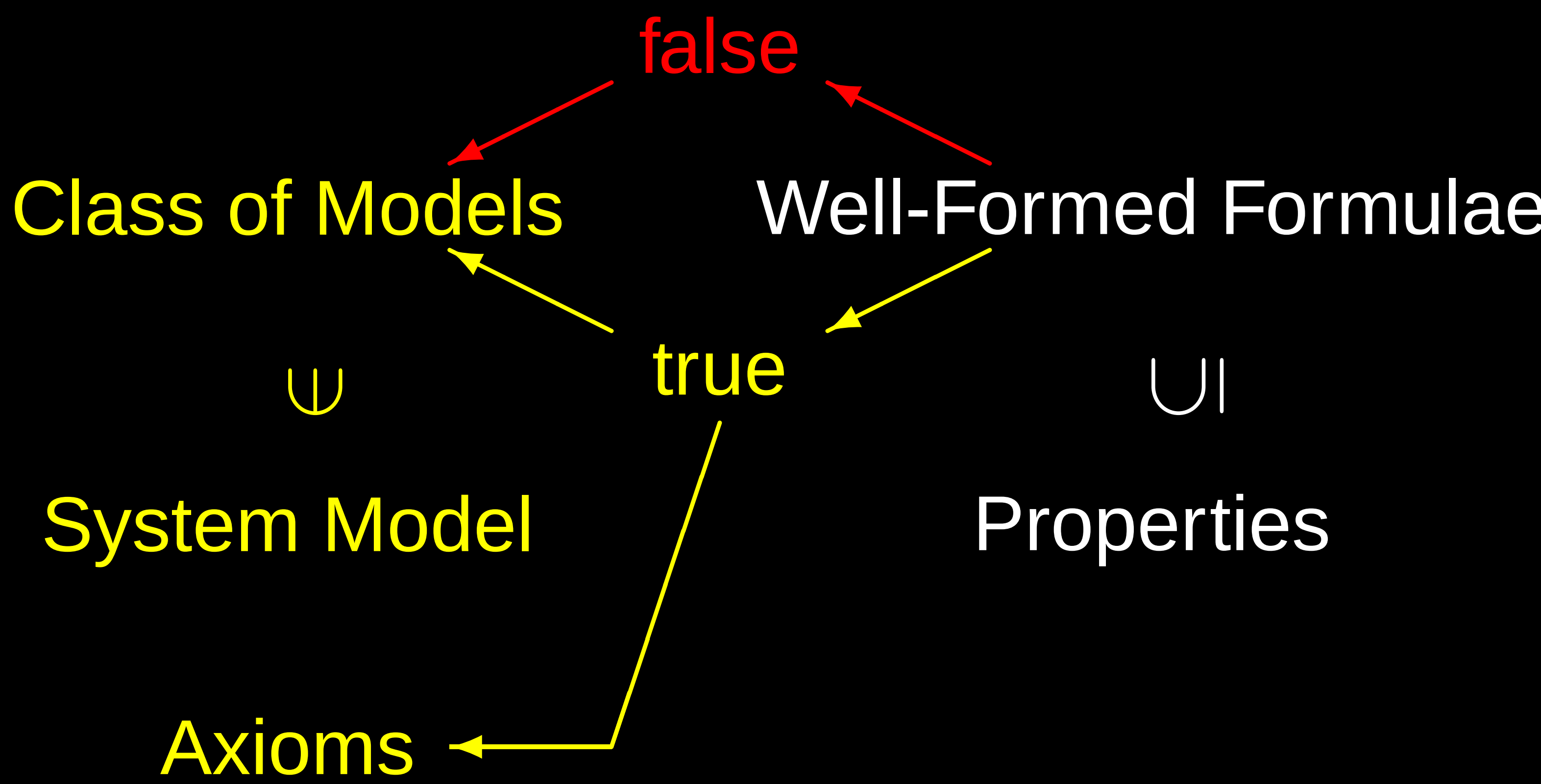

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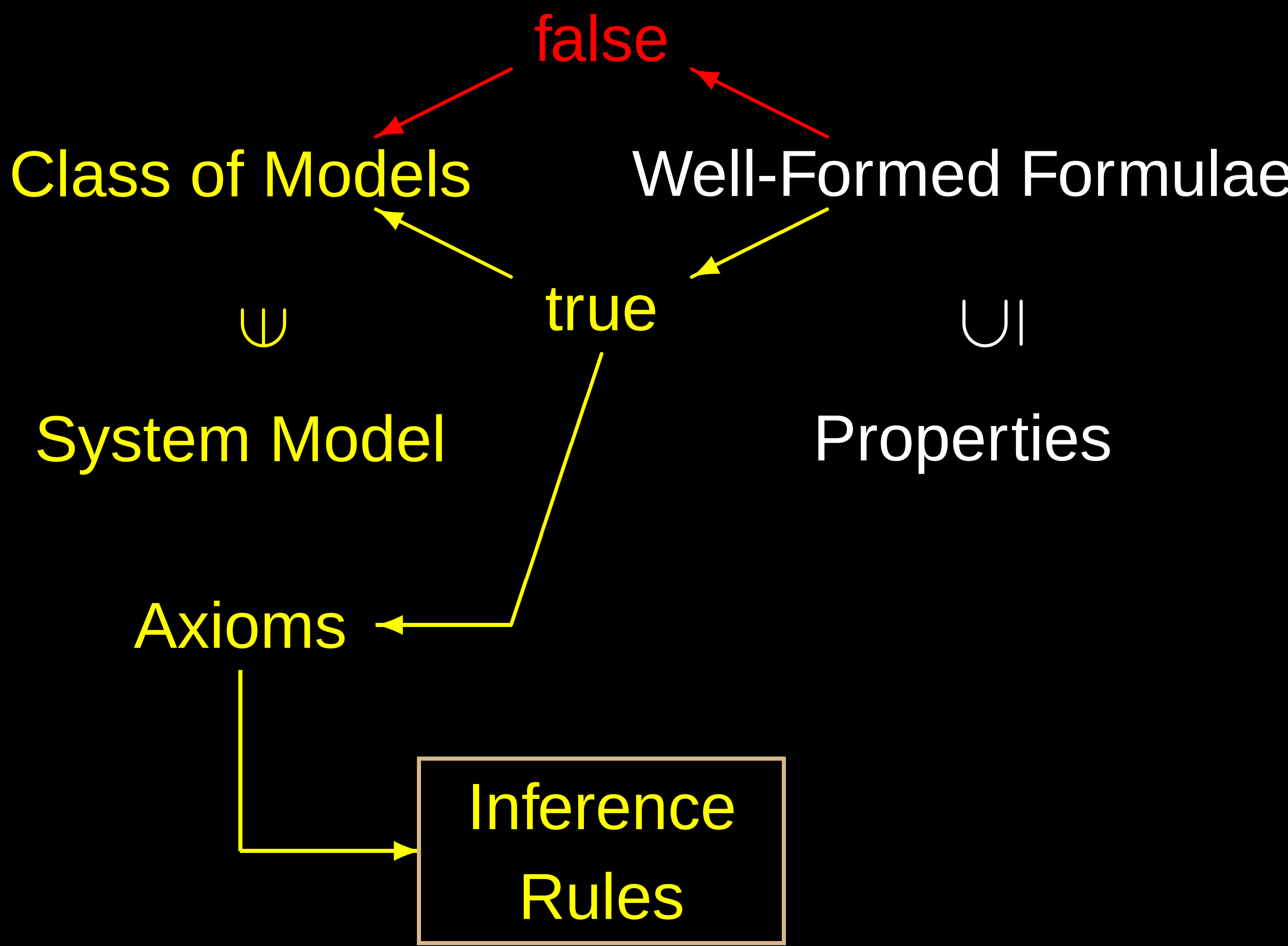

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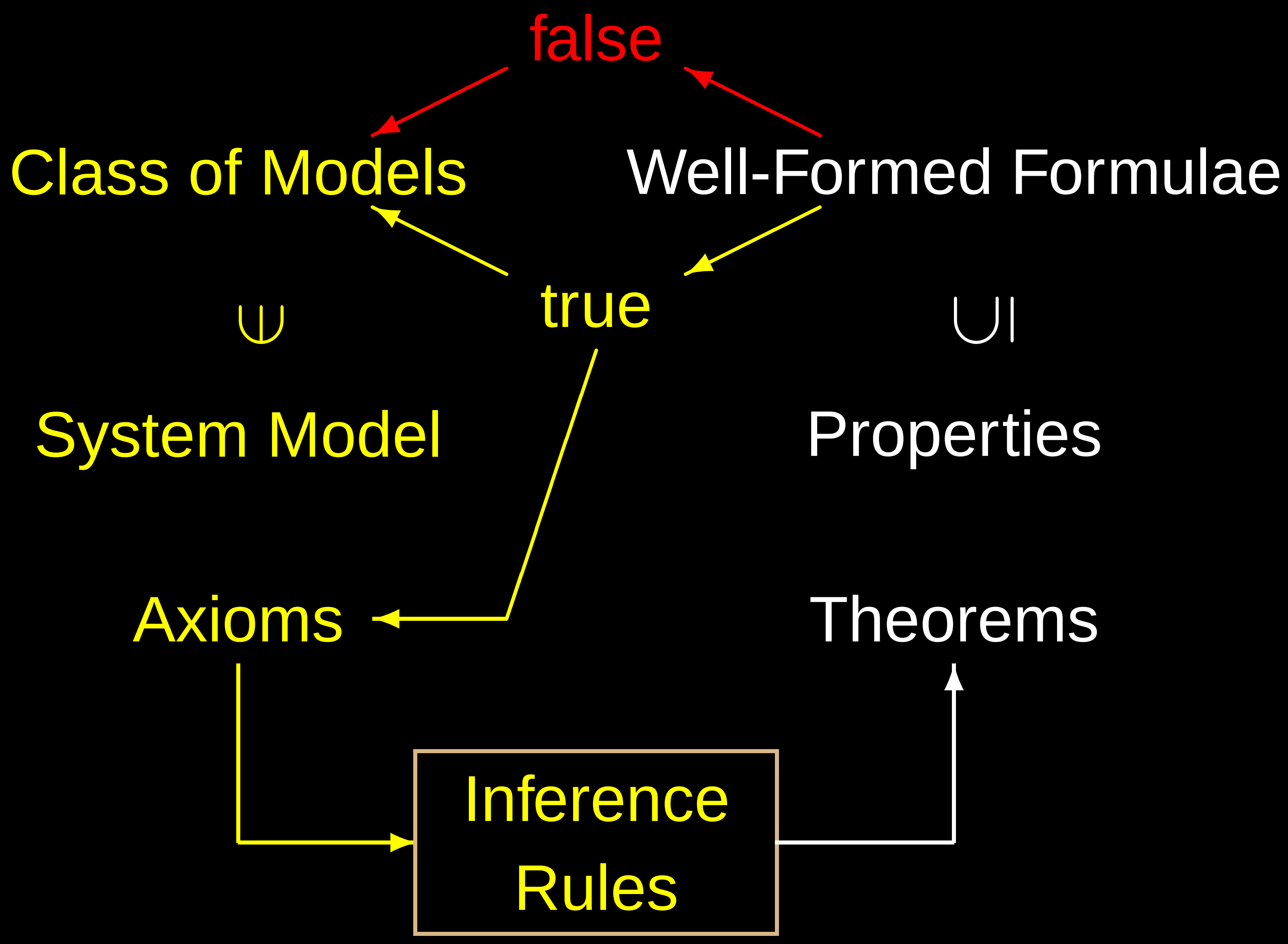

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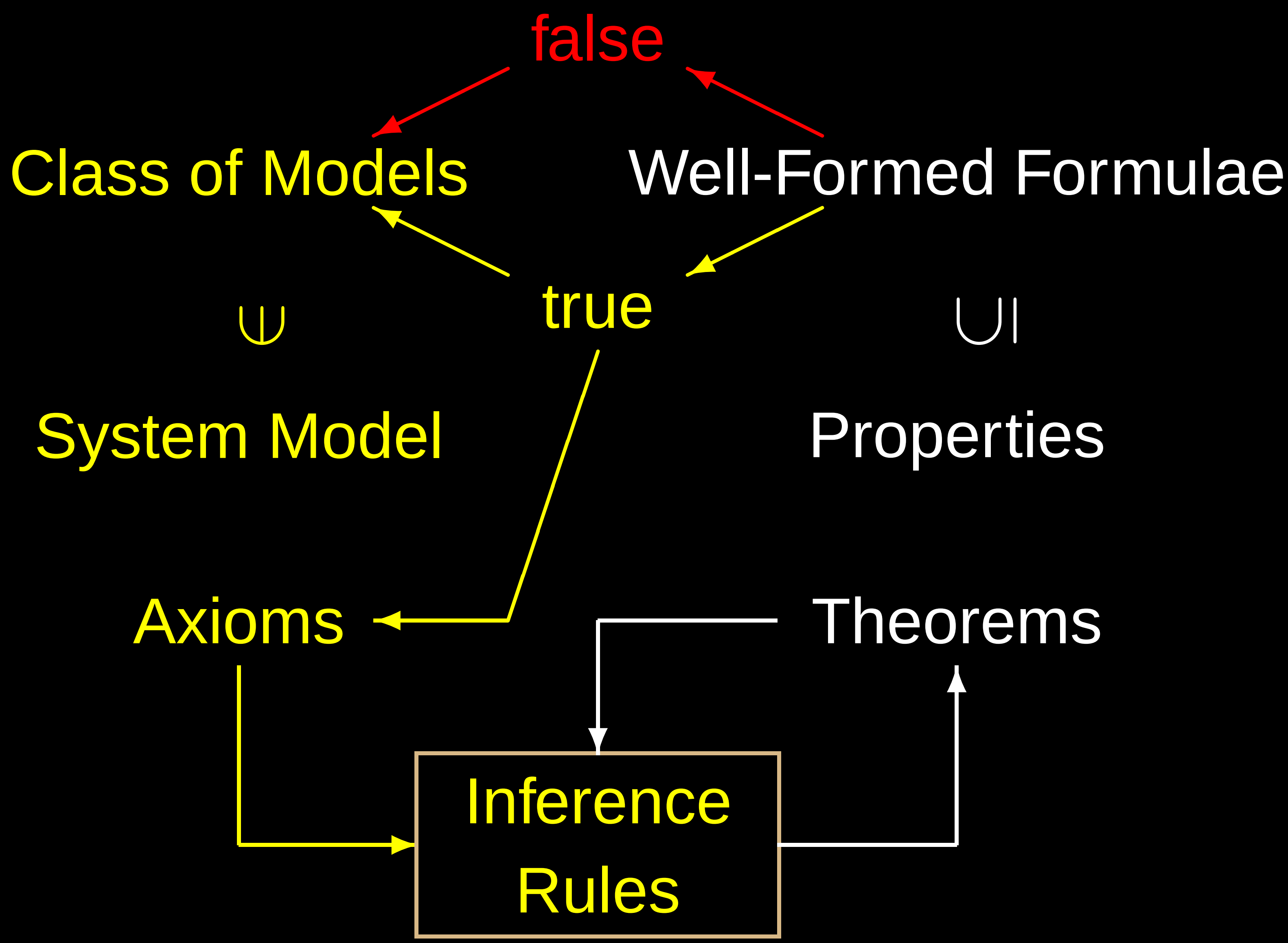

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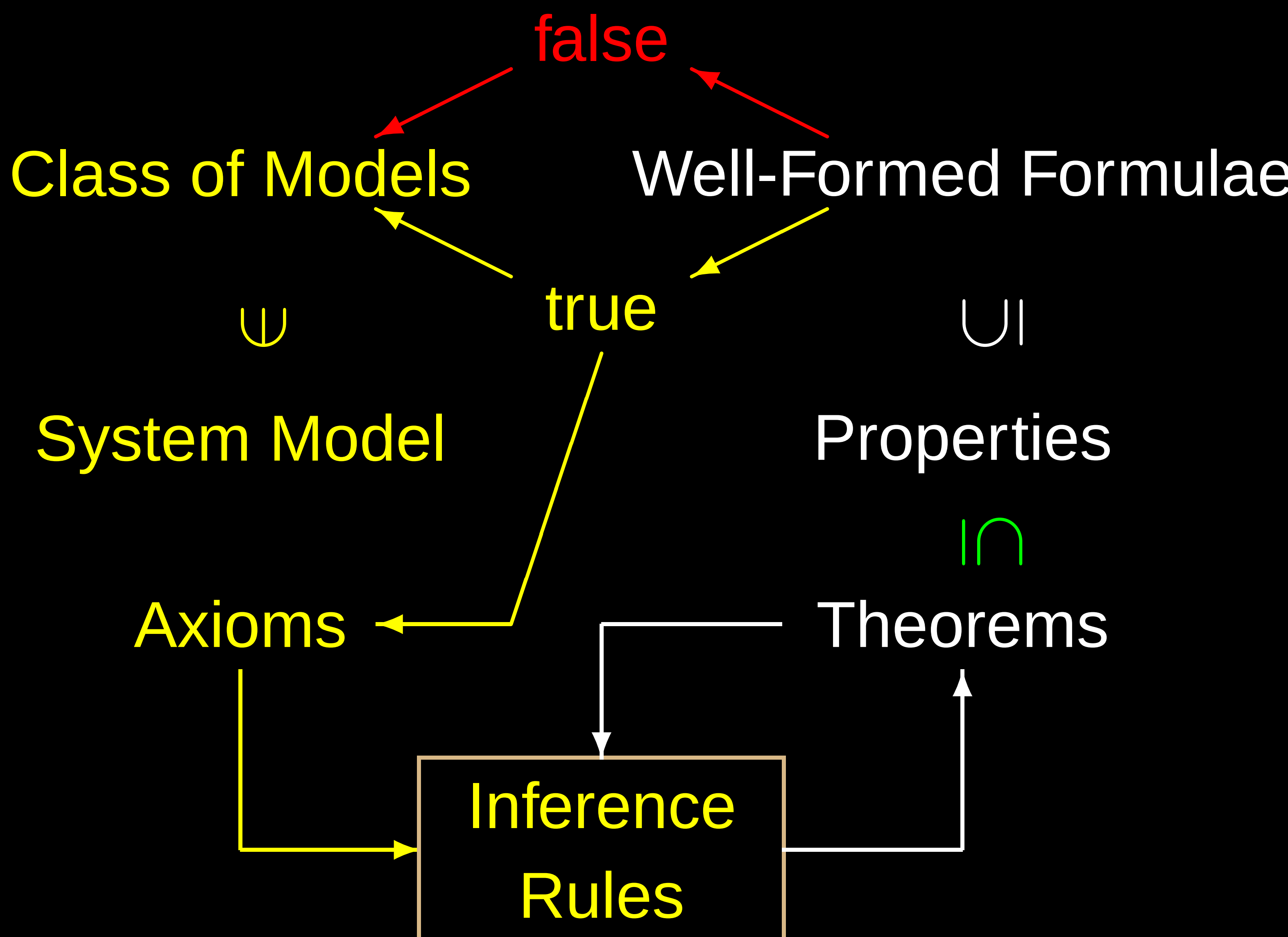

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nondeterministic rules $\Longrightarrow$ rule disjunction

Reactive Behaviour

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NEXT does not require that the action is taken on the next cycle, but rather that it is taken before any other user action

Reactive Behaviour

$$(\mathit{stimulus}\ t) \wedge \mathit{NEXT}\ \mathit{reaction}\ t$$

To target the generic user model to a particular device, it is applied to a concrete list in SML

$$[(\mathit{stimulus}_1, \mathit{reaction}_1);\ \ldots;\ (\mathit{stimulus}_n, \mathit{reaction}_n)]$$

Reactive Behaviour

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$$[(stimulus_1, reaction_1);\ \ldots;\ (stimulus_n, reaction_n)]$$

Example: $[(light, push\_button);\ (wait\_msg, pause);\ (card\_msg, take\_card);\ (cash\_msg, take\_cash)]$

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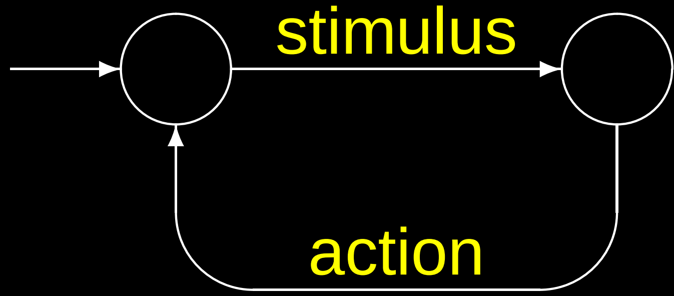

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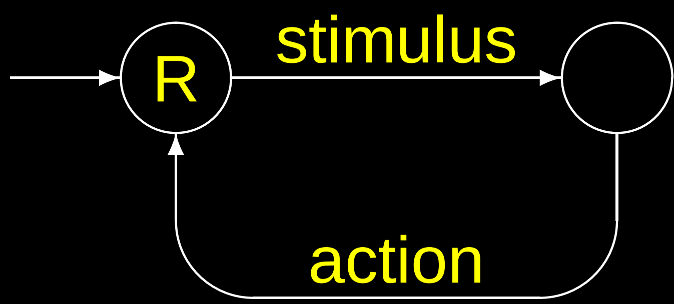

$R_1 = R/f_1$ where $f_1(\text{stimulus}) = \text{light}$
$f_1(\text{reactions}) = \text{push\_button}$

$$[(stimulus_1, reaction_1); \ldots; (stimulus_n, reaction_n)]$$

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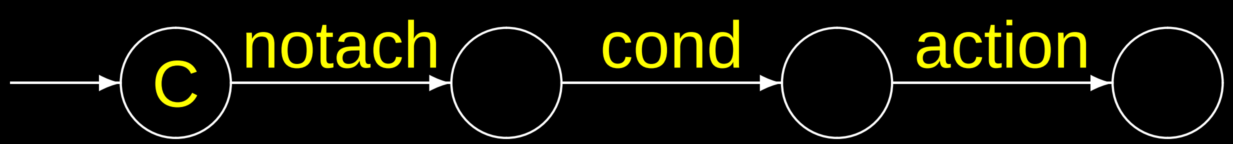
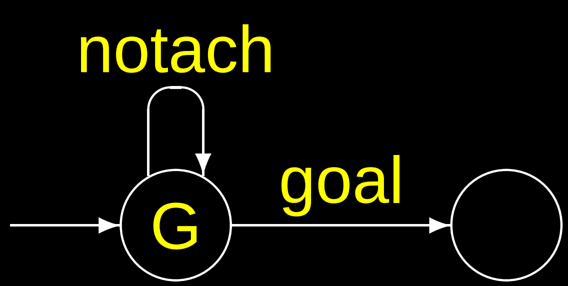
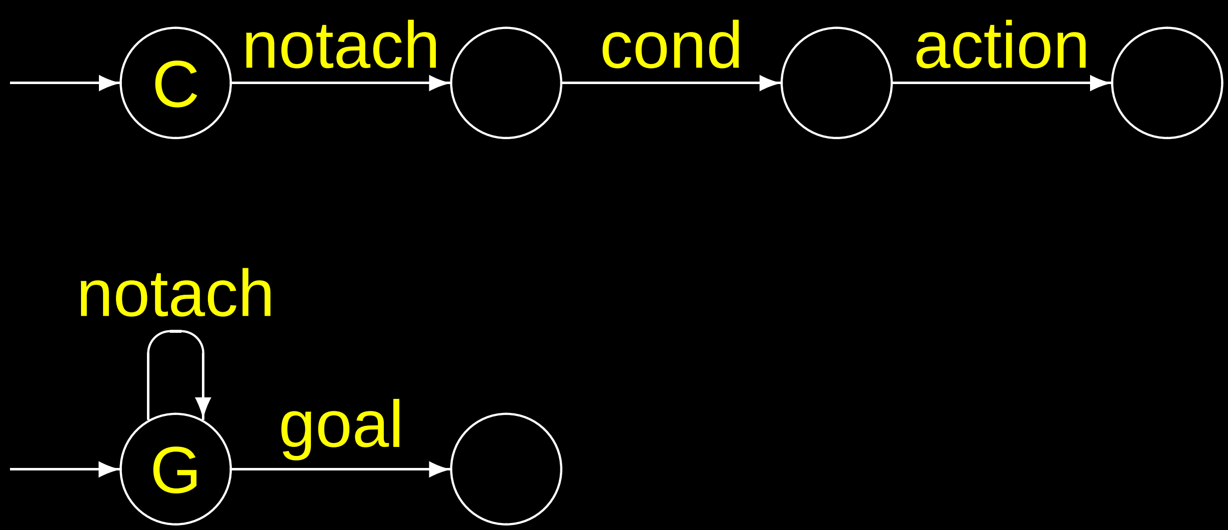




Completion

$$\mathit{if}\ (((\mathit{invariant}\ t) \wedge (\mathit{goalachieved}\ t)) \vee ((\mathit{finished}\ (t-1))$$
$$\mathit{then\ action\ finished}\ t$$
$$\mathit{else}\ \text{—}\mathit{disjunction\ of\ nondeterministic\ rules}\text{—}$$

Invariant: $\mathit{VALUE\ possession}\ t \geq \mathit{VALUE\ possession}\ 1$



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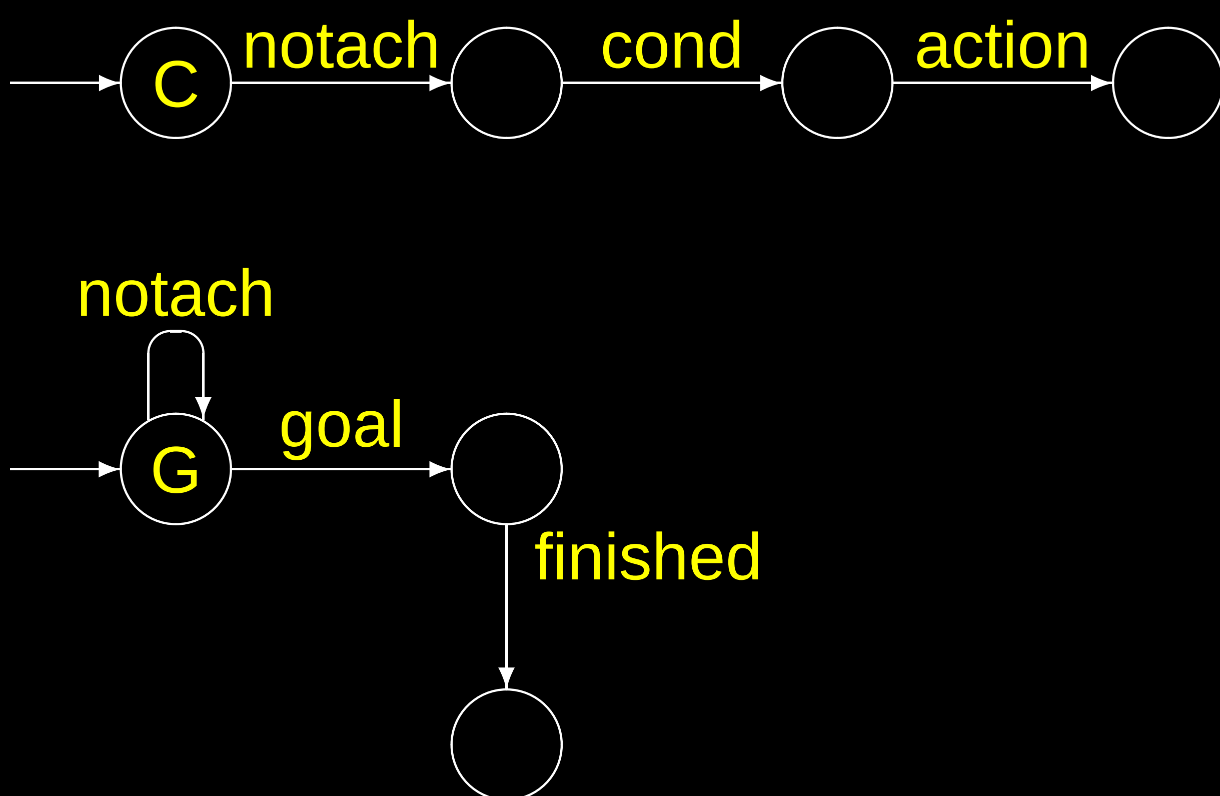

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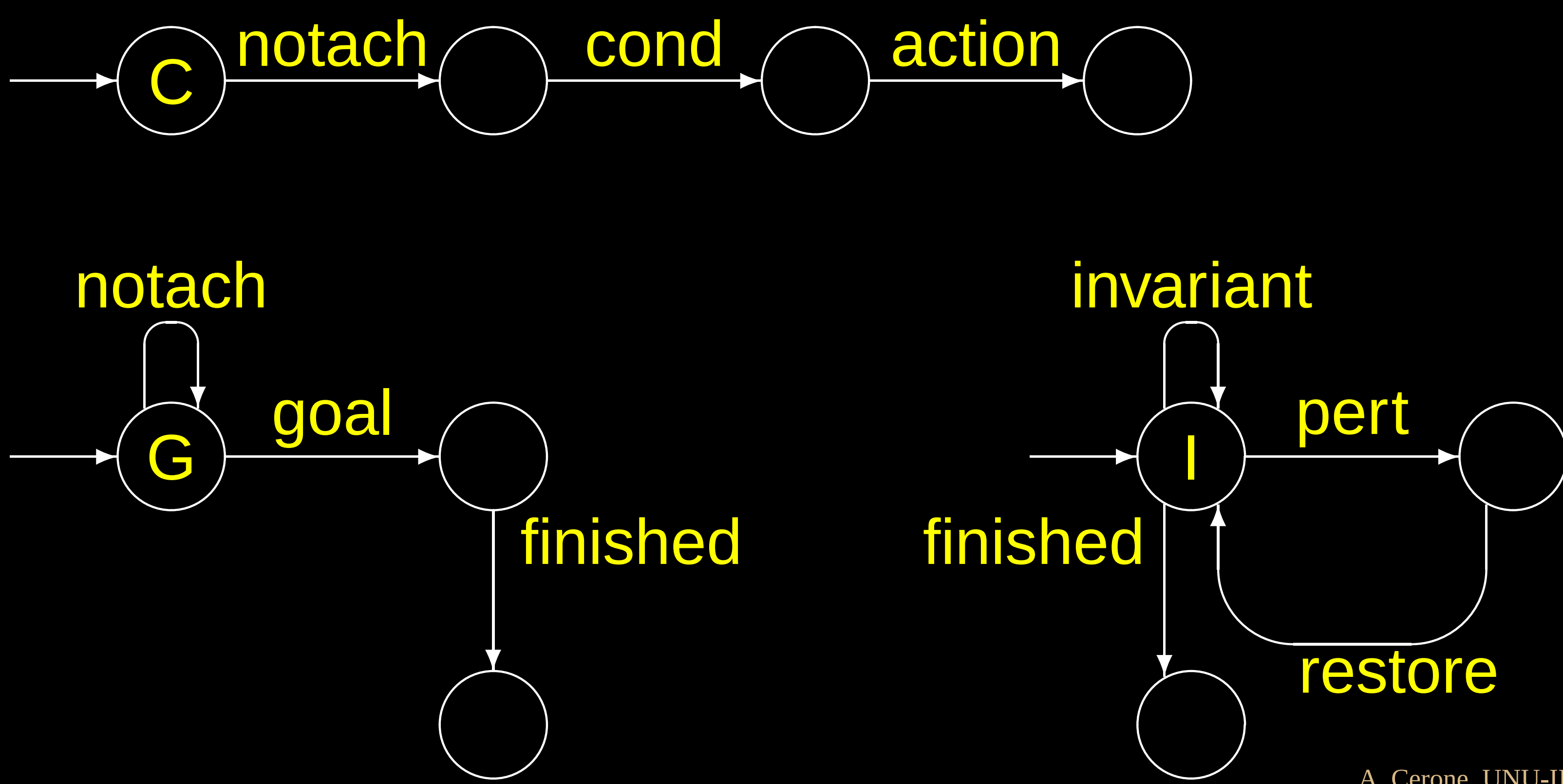

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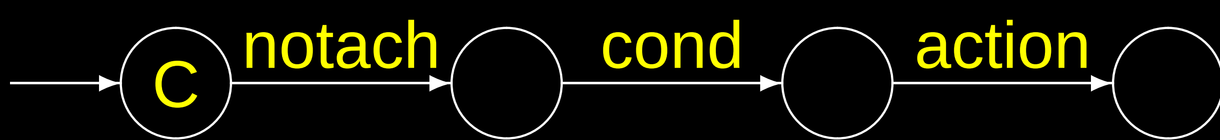
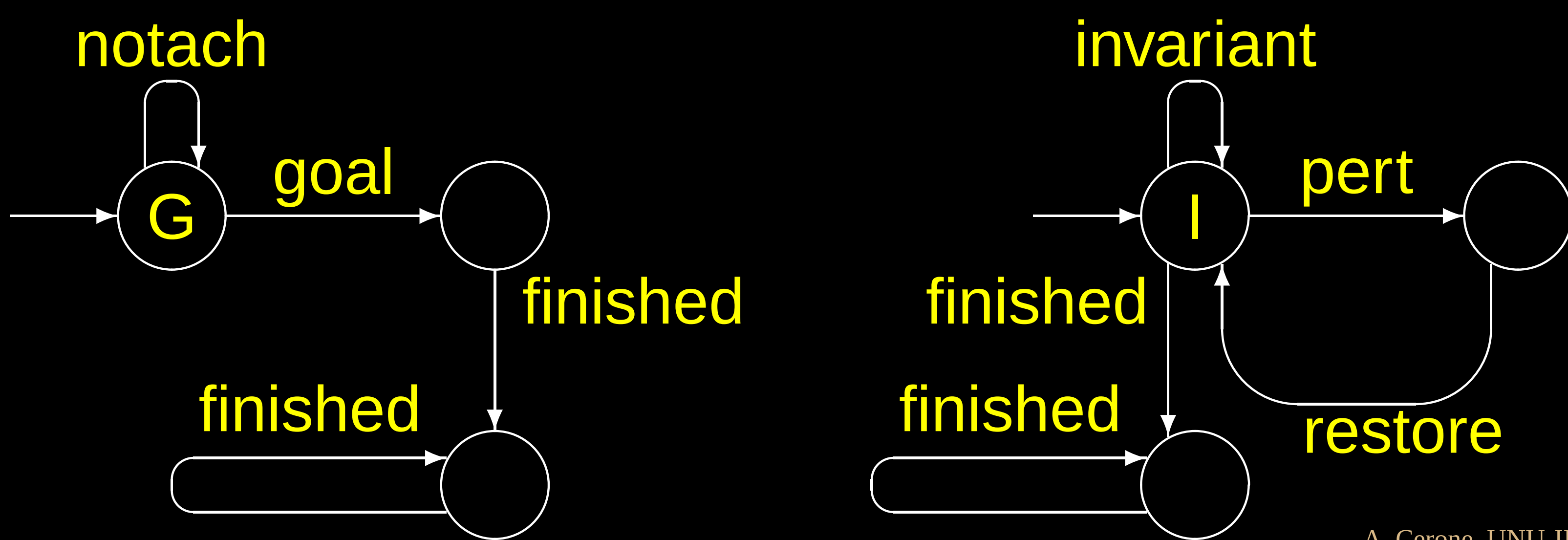
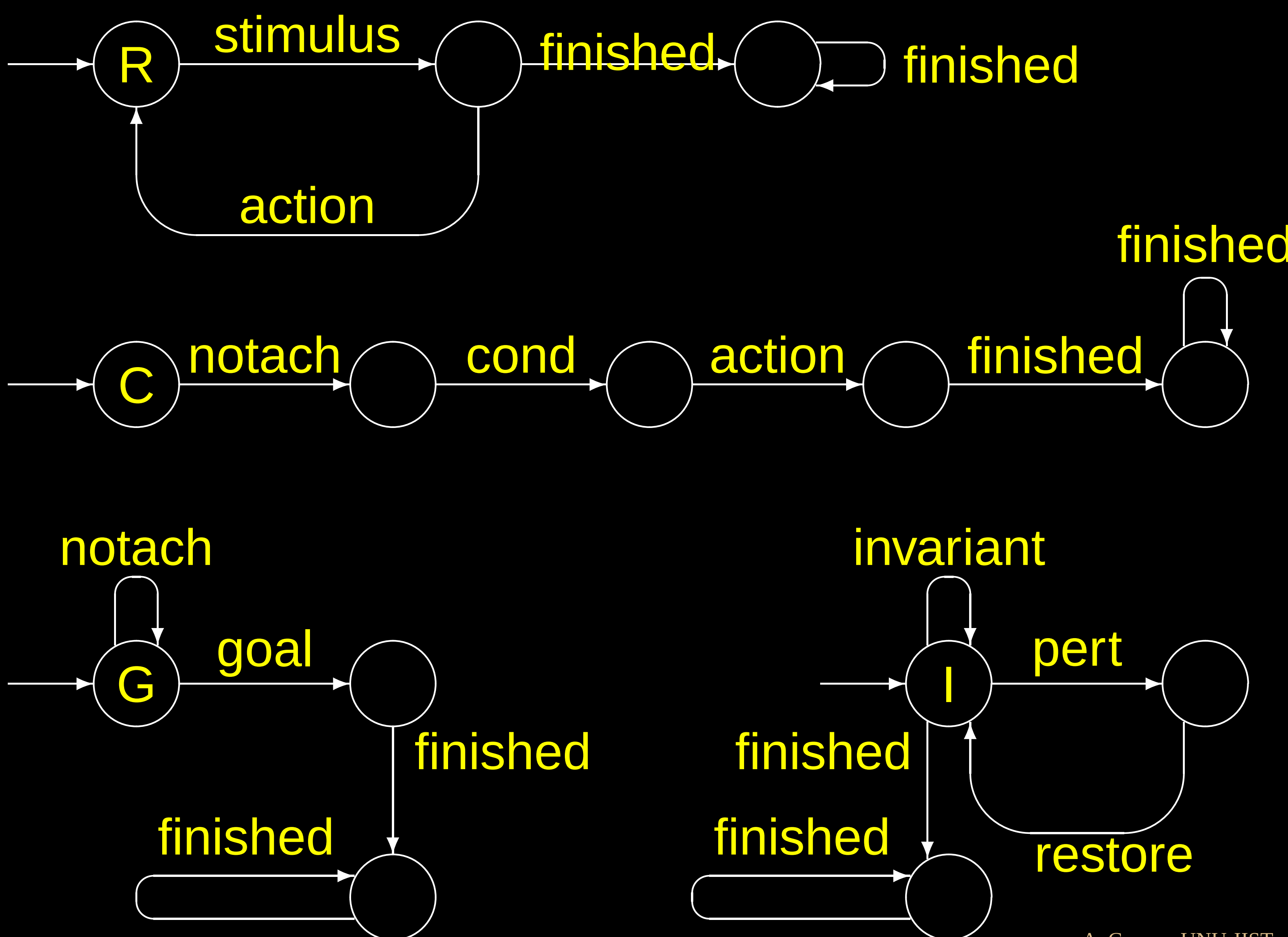




CSP Architecture



User Model

HOL

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HOL

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User Model

- HOL
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User Model

HOL

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CSP

$$
\begin{aligned}
\mathsf{U} \quad = \quad & \mathsf{R}_1 \;\|\; \ldots \;\|\; \mathsf{R}_m \;\| \\
& ((\mathsf{C}_1 \;\|\; \mathsf{G}) \,|[\{goal, finished\}]|\, \ldots \\
& \ldots \,|[\{goal, finished\}]|\, (\mathsf{C}_n \;\|\; \mathsf{G})) \;\| \\
& \mathsf{I}_1 \;\|\; \ldots \;\|\; \mathsf{I}_s
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& \mathsf{I}_1 \;\|\; \ldots \;\|\; \mathsf{I}_s
\end{aligned}
$$

What's missing?

EXERCISE

How to guarantee that all reactive behaviours and communication goals are performed atomically within the user model?

Formal Verification

HOL — Correctness Theorem

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$$\begin{array}{l}
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CSP

– Overall system

$\mathsf{OverallSystem} = \mathsf{U}\ \|\ \mathsf{Device}$

– Temporal Logic Formula

$\Box\Diamond\,\mathsf{finished}$ checked on OverallSystem

Classes of User Errors

Errors detected by attempts to prove the task completion error

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Classes of errors defined in terms of their cognitive causes rather than their effects:

- post-completion errors
- communication-goal errors
- device delay errors

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Error still present if a warning after goal achieved remind the user to do the completions tasks

Communication Errors

User discharges communication goals in an order different from the one required by the device

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Design Principle: the device must not require a specific order for the communication goal actions

Communication Errors

User discharges communication goals in an order different from the one required by the device

It emerges because of communication rule removed too early $\Longrightarrow$ activate abort rule

Design Principle: the device must not require a specific order for the communication goal actions

Error still present if a message tell the user the right order

Device Delay Errors

User discharges outstanding communication goals during device delay

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Design Principle: the device delay can only occur when there is no outstanding communicatin goal in the presence of a “wait” warning causing a “pause” reaction

TP vs. MC

- Theorem Proving

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- Theorem Proving
  - automated correctness proof

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  - informal reasoning to detect errors

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  - informal reasoning to detect errors
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  - general correctness: $\Box\Diamond$ finished
  - post-completion correctness: $\Box\Diamond$ invariant
  - automatically generated counterexample allows error detection and correction

Examination — Architectures

SOAR and PUMA

- Seminars
  - Theorem proving and informal reasoning for usability studies
  - The SOAR cognitive architecture
- Reports
  - CSP model of the PUMA cognitive architecture

Examinations

Seminar 1 — Full OCM for ATC

Topic: Operator Choice Model for ATC

Full OCM model for the ATC

- D. Leadbetter, P. Lindsay, A. Hussey, A. Neal and M. Humphreys
  Towards Towards Model Based Prediction of Human Error Rates in Interactive Systems, 2000
- A. Hussey, D. Leadbetter, P. Lindsay, A. Neal and M. Humphreys
  Modelling and Hazard Identification in an Air-Traffic Control User-Interface, 2000
- S. Connelly, P. Lindsay, A. Neal and M. Humphreys
  A formal model of cognitive processes for an Air Traffic Control Task, 2001

Seminar 2 — Mode Confusion

Topic: Mode Confusion

Formal analysis of mode confusion

- S. P. Miller and J. N. Potts
  Detecting Mode confusion Through formal Modelling and Analysis,
  1999
- N. Leveson, L. D. Pinnel, S. D. Sandys, S. Koga and J. D. Reese
  Analysing Software Specification for Mode Confusion Potential,
  1998
- R. W. Butler, S. P. Miller, J. N. Potts and V. A. Carreno
  A Formal Methods Approach to the Analysis of Mode Confusion,
  1998

Seminar 3 — PUMA

Topic: PUMA Work

Theorem proving and informal reasoning for usability studies

- P. Curzon and A. Blandford
  Detecting Multiple Classes of User Errors, 2001
- P. Curzon and A. Blandford
  From a Formal User Model to Design Rules, 2002
- P. Curzon and A. Blandford
  Formally Justifying User-Centred Design Rules: a Case Study on Post-completion Error, 2004

Seminar 4 — SOAR

Topic: SOAR

The SOAR cognitive architecture (for one or more PhD students)

- SOAR Home Page
  http://sitemaker.umich.edu/soar/
- The SOAR Tutorial
  http://sitemaker.umich.edu/soar/documentation_and_links
  Part 1 | Part 2 | Part 3 | Part 4 | Part 5 | Part 6

Report 1 — FM of Full ATC

Topic: Operator Choice Model

Formal model of the full OCM for ATC

using CSP or other formalism, possibly running simulation using a tool

- D. Leadbetter, P. Lindsay, A. Hussey, A. Neal and M. Humphreys
  Towards Model Based Prediction of Human Error Rates in Interactive Systems, 2000
- S. Connelly, P. Lindsay, A. Neal and M. Humphreys
  A formal model of cognitive processes for an Air Traffic Control Task, 2001
- Antonio Cerone, Simon Connelly and Peter Lindsay.
  Formal Analysis of Operator Behavioural Patterns in Interactive Systems, submitted

Report 2 — Cooperative TM

Topic: Task Models

Formal Analysis of Cooperative Task Models

Discussion of the papers' differences and limitations and propose possible extensions

- F. Paternò, C. Santoro and S. Thamassebi
  Formal models for Cooperative Tasks: Concepts and an Application for En-route Air Traffic Control
- V. M. R. Penichlet, F. Paternò, J. A. Gallud and M. D. Lozano
  Collaborative Social Structures and Task Modelling Integration
- D. Pinelle and C. Gutwin
  Task Analysis for Groupware Usability Evaluation: Modeling Shared Workplace Tasks with Mechanics of cCllaboration

Report 3 — PUMA

Topic: PUMA Work

CSP model of the PUMA cognitive architecture

Build a case study and formally analyse it with a tool (e.g. CWNC)

- P. Curzon and A. Blandford
  Using a Verification System to Reason about Post-Completion Errors, 2000
- P. Curzon and A. Blandford
  Reasoning about Order Errors in Interaction, 2000
- P. Curzon and A. Blandford
  Detecting Multiple Classes of User Errors, 2001

References

Cognitive Architecturess

- []:

[Newel et al. 91]

Allen Newell, Gregg Yost, John Laird, Paul Rosembloom, Ekkehard Altmann.
Formaulating the problem-space computational model.
In R. F. Rashid (ed) *CMU Computer Science: a 25th Anniversary Commemorative*, Chapter 11, ACM Press, 1991.

- Problem Space
- Cognitive Architectures

[Newel et al. 87]

Allen Newell, John Laird, Paul Rosembloom.
SOAR: an architecture for general intelligence.
Artificial Intelligence 33, 1987, pages 1–64.

- SOAR

[Young et al. 89]

Richard Young, T. R. G. Green, Tony Simon. *Programmable user models for predictive evaluation of interface design*. In K. Bice and G. Lewis (eds) *Proceedings of CHI'89: Human Factors in Computing Systems*, ACM Press, 1989, pages 15–19.

- PUM

[Curzon et al. 01]

Paul Curzon, Ann Blandford.
Detecting multiple classes of user errors.
In *Proceedings of EHCI'01*, LNCS 2254,
Springer, 2001, pages 57–71.

- Detecting Errors