A Survey of Reactive Synthesis

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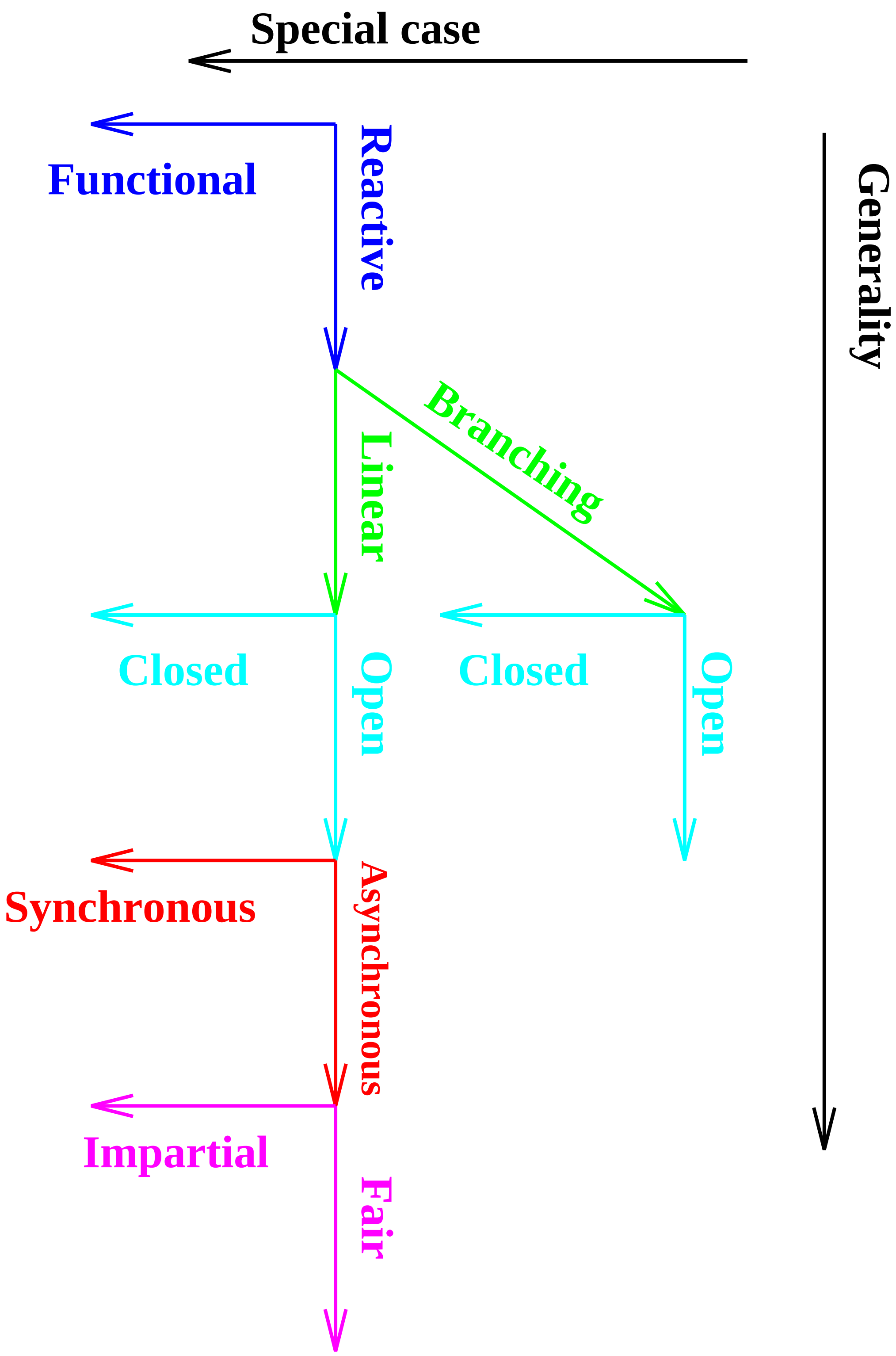
Problem:

Derive reactive module
from temporal specification

Solutions:

Automata theory
Model building
Proof theory
Constraint satisfaction

Road Map



Special case
Generality
Functional
Reactive
Branching
Linear
Closed
Open
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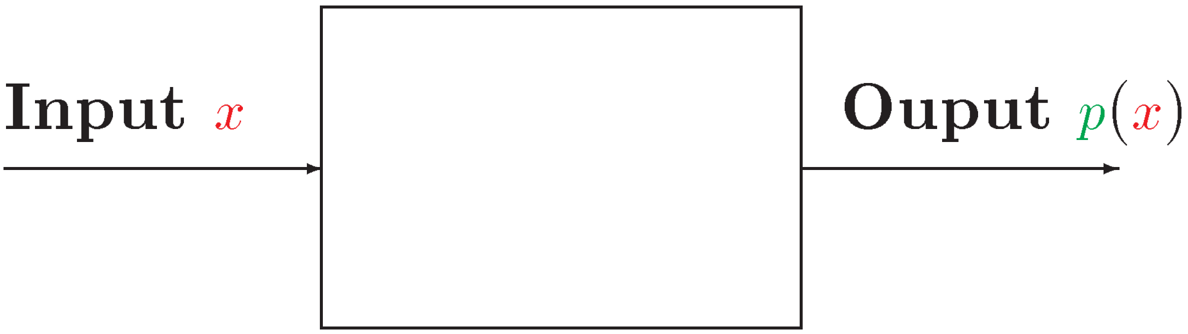
Synchronous
Asynchronous
Impartial
Fair

Functional Synthesis

First-order specification $\forall x\ \exists y \cdot \varphi(x, y)$

Find program $p(x)$ such that

$$\forall x \cdot \varphi(x, p(x))$$



- Extraction of programs from proofs
- Program transformations

Works on Functional Synthesis

[Curry-Howard 69,80]	Formulas as types
[Burstall-Darlington 77]	Transformations
[Manna-Waldinger 80]	Tableau
[Mints-Tyugu 82]	Priz
[Coquand-Huet 85]	Coq
[Constable 86]	Nuprl
[Hayashi-Nakano 88]	PX
[Smith 90]	KIDS
[Abramsky 90]	Linear Logic
[Murthy 92]	Continuations
[Lowry 95]	Amphion

Functional Synthesis Example

Prove

$$\forall x,\ \epsilon > 0\ \exists y \cdot (y^2 \leq x < (y+\epsilon)^2)$$

Extract

$$
\begin{aligned}
&\mathbf{sqrt}(x,\epsilon) = \\
&\qquad \text{if } \epsilon^2 > x \ \text{ then } 0 \ \text{ else} \\
&\qquad \text{let } \ z = \mathbf{sqrt}(x, 2\cdot\epsilon) \text{ in} \\
&\qquad\qquad \text{if } \ (z+\epsilon)^2 \leq x \\
&\qquad\qquad \text{then } \ z+\epsilon \\
&\qquad\qquad \text{else } \ z
\end{aligned}
$$

From a constructive proof

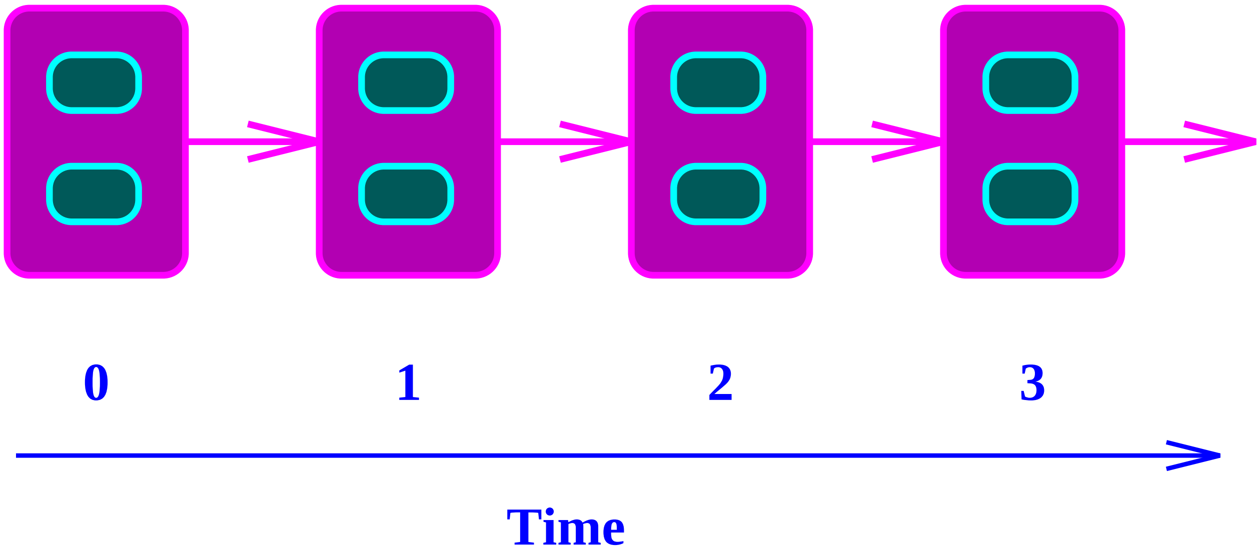
Induction = Recursion

Resolution = Case distinction

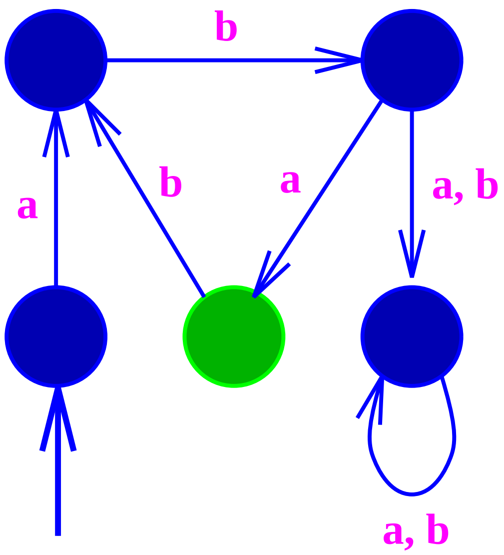
Cut = Let-binding

Reactive Synthesis

Characterized by ongoing behaviour

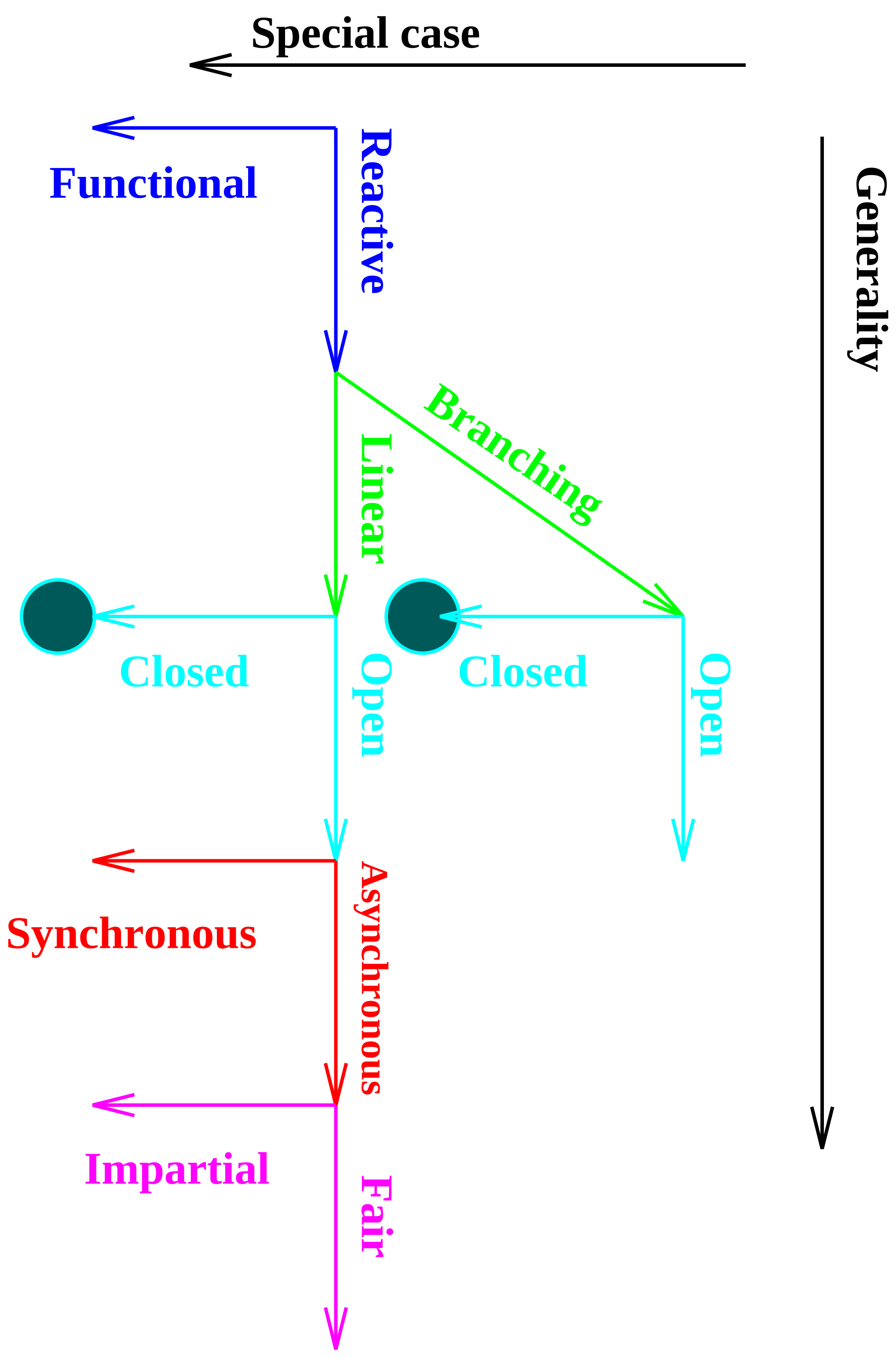


Specification φ is temporal



$a;$
loop forever do
$\left[b;\ \ a;\ \ b\ \right]$

Road Map



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Closed System Synthesis

Satisfiability problem

$$\exists y \cdot \varphi(y)$$

LTL solution [Manna-Wolper 81]

- Build tableau (PSPACE)
- Check non-emptiness (LINEAR)
- Extract CSP program from model

CTL solution [Clarke-Emerson 81]

- Build branching tableau (EXPTIME)
- Check non-emptiness (QUADRATIC)
- Extract test-and-set from model

Closed System Synthesis

ω-regular solution
[Anuchitanukul 95 (thesis)]

- Build Büchi automaton $\mathcal{B}$ (PSPACE)
- Extract fair transition system $\mathcal{T}$
  Nondeterministic (LINEAR)
  Each transition deterministic (EXPONENTIAL)

Features:

- Maximal synthesis

$$L(\mathcal{T}) = L(\mathcal{B})$$

- Minimal degree of parallelism
  - static
    FTS $\Rightarrow$ $|\mathcal{T}| = 2$
  - dynamic
    DSTS $\Rightarrow$ optimization algorithm

Hierarchy of Fair Transition Systems

FTS	Fair transition system
2FTS	FTS with 2 transitions
Buchi	ω-regular
STS	Compassionate
WTS	Just
DTS	Deterministic
DSTS	Deterministic compassionate
D-Buchi	
DWTS	Deterministic just

Closed Multiprocess Synthesis

[Attie-Emerson 89]

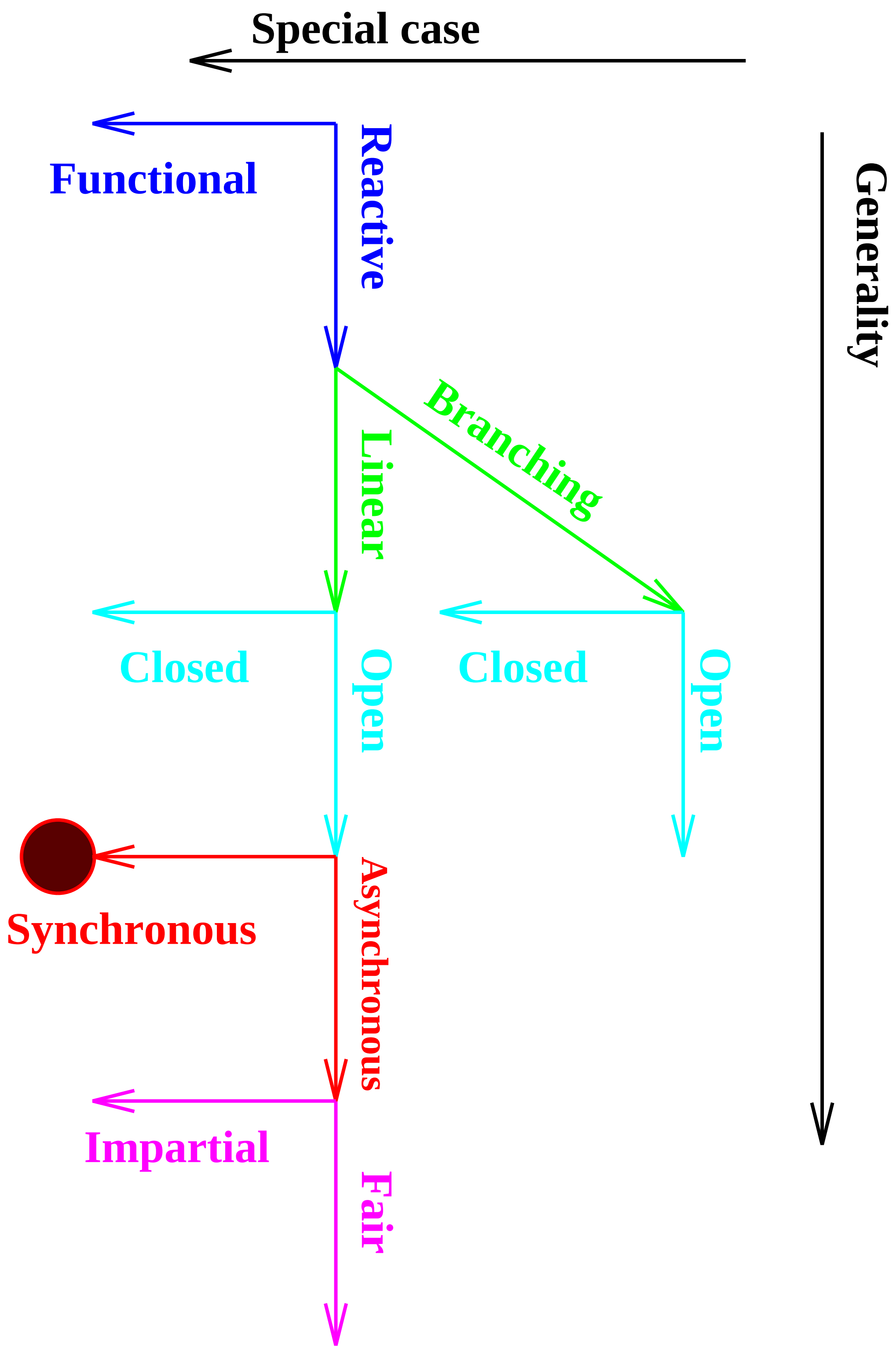
Problem: Combinatorial explosion encountered for 3-4 processes

Solution: Use multiprocess CTL with extra process quantifiers:

$$\bigwedge_{i,j} (R(i,j) \rightarrow \varphi) \qquad\qquad \bigvee_{i,j} (R(i,j) \wedge \varphi)$$

Benefit: Uniform synchronization skeletons are derived for any number of processes

Road Map



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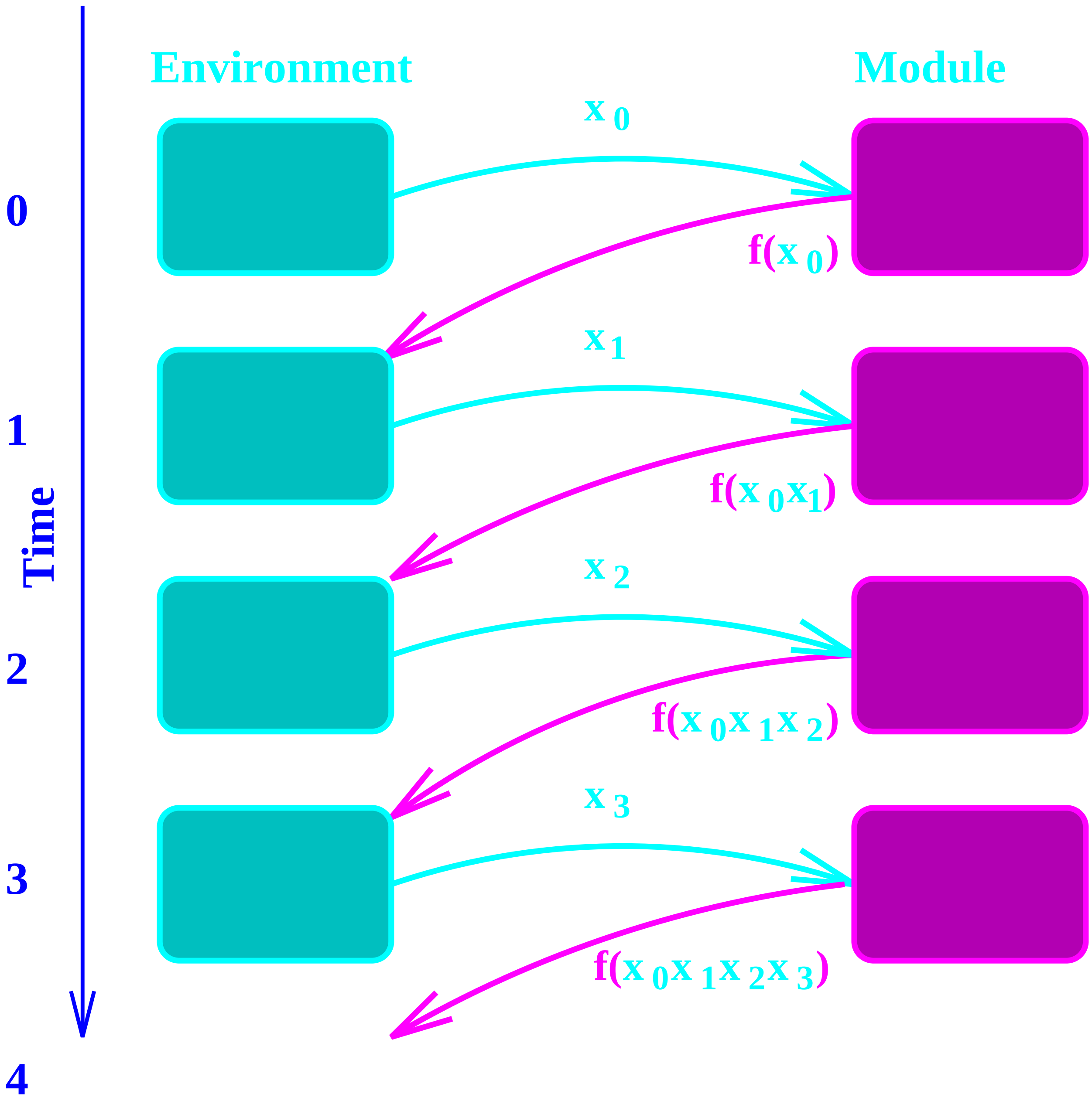
Open Synchronous

Temporal specification $\forall x \; \exists y \cdot \varphi(x, y)$.

Find program $f(x)$ such that

$$\forall x \cdot \varphi(x, f(x))$$



Church's Problem [Church 62]

Summary of early digital synthesis and verification

Specification $\mathcal{C}(X : I^\omega, Y : J^\omega)$ in "restricted recursive arithmetic"

Find operator $f : I^\omega \to J^\omega$
such that

$$\forall X \cdot \mathcal{C}(X, f(X))$$

is valid

Requirements

(I) f may not depend on the future

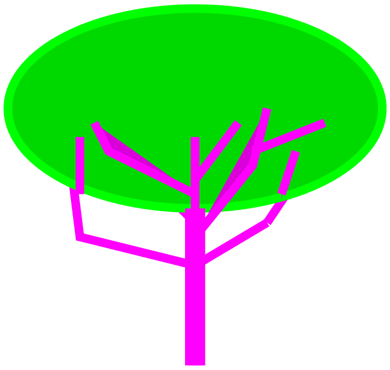
(II) f may not depend on the far past

Solution 1: Tree Automata

[Rabin 72]

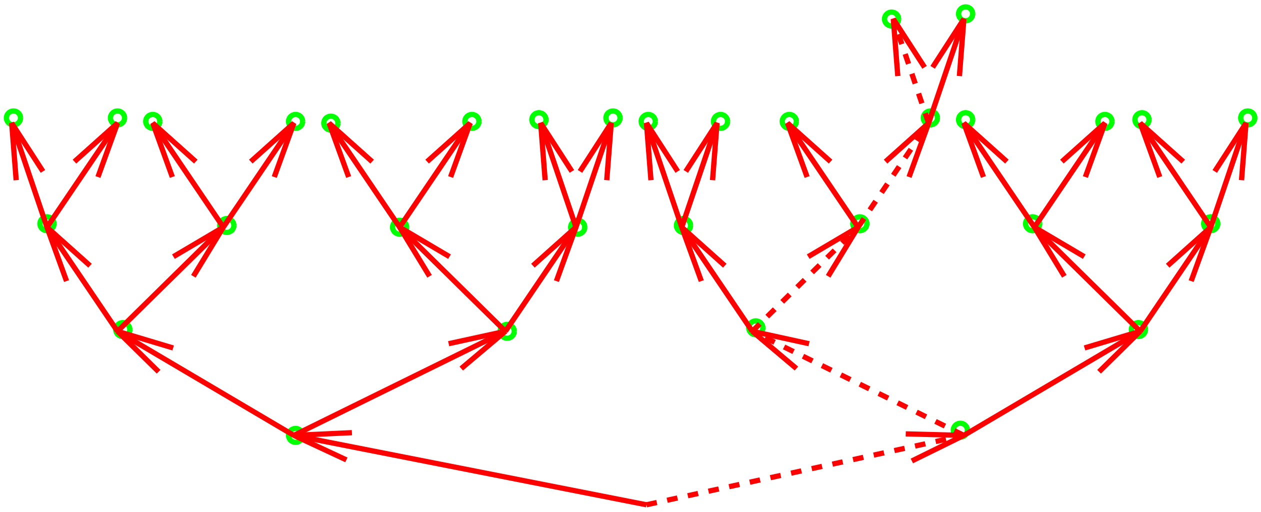
[Emerson-Jutla 88]

[Pnueli-Rosner 89]



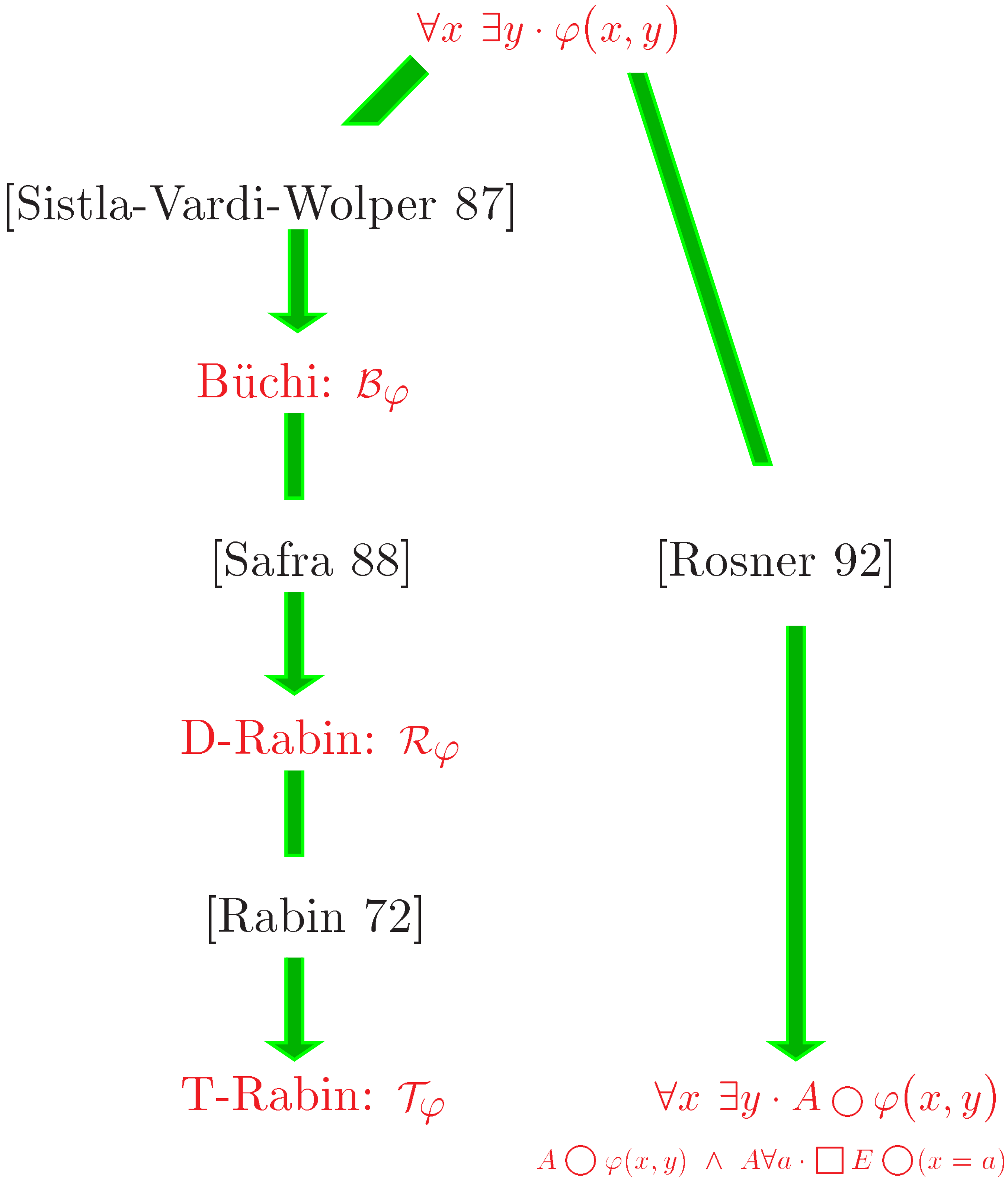
X-player chooses branch

Y-player chooses labeling



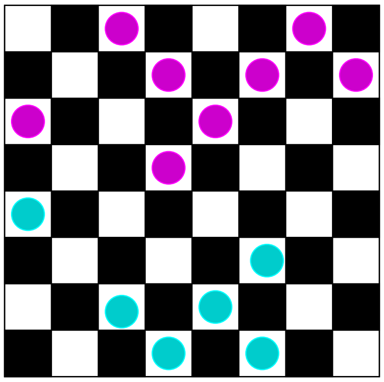
- Realizability = Non-emptiness
- Extract deterministic transducer from model
- Complexity: 2EXPTIME

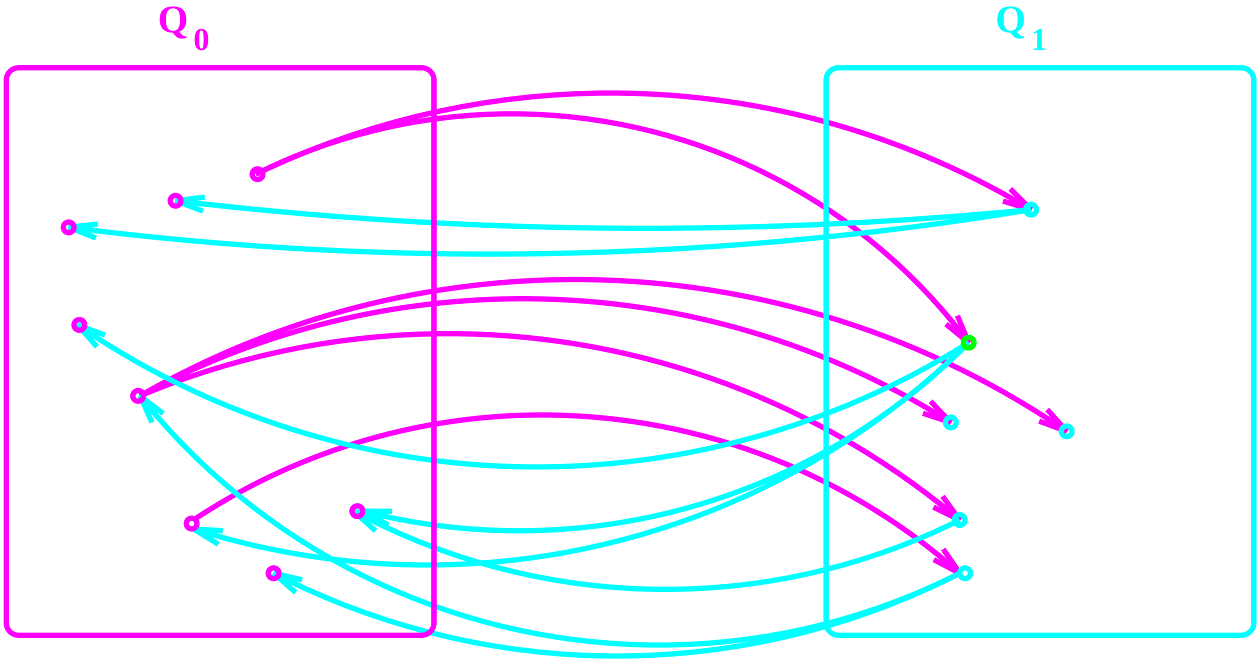
Specification $\mapsto$ Tree Automaton



Solution 2: Game Automata

[Gale-Stewart 53]
[Büchi-Landweber 69]
[McNaughton 93]
[Thomas 95][Lescow 95]





Specification $\subseteq (Q_0Q_1)^\omega$

[Davis 64], [Martin 75]:

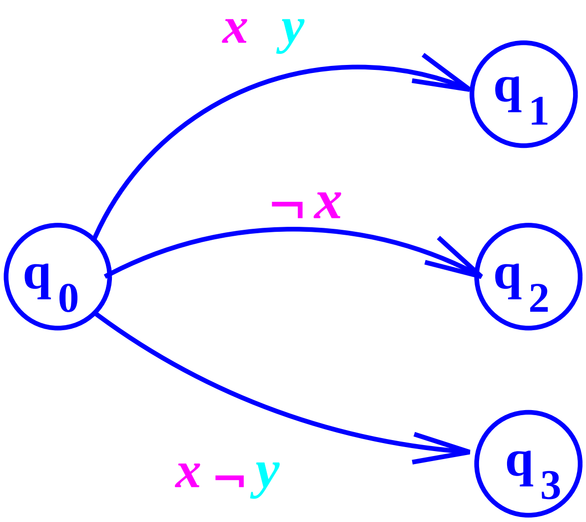
Sequential games $\subset$ Borel games

are determined

Specification $\mapsto$ Game

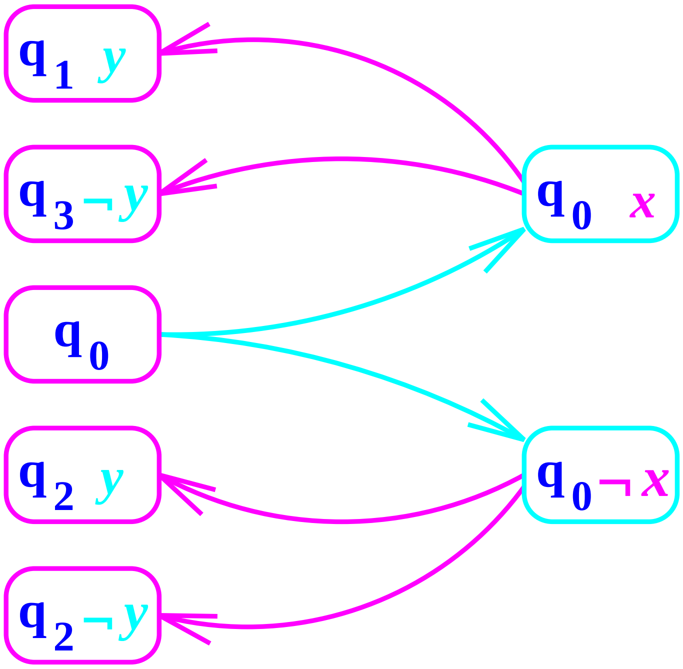
$\forall x \exists y \cdot \varphi(x, y)$

[Sistla-Vardi-Wolper 87]
[Safra 88]



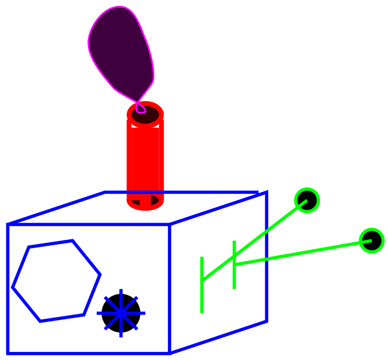
D-Automaton $\mathcal{R}_\varphi$

Game :



Solution 3: Control Synthesis

[Ramadge-Wonham 87]
[Thistle-Wonham 94]
[Maler-Pnueli-Sifakis 95]



Discrete Event System $\mathcal{P}$:

Σ	controllable actions
Q	system states
q_0	initial state
$\delta_{\mathcal{P}} : Q \times \Sigma \to 2^Q$	transition function
$L : Q \to 2^{\mathrm{Prop}}$	state labeling

Find controller

$$\mathcal{C} = \langle M,\ m_0,\ \delta_{\mathcal{C}} : M \to \Sigma \times M \rangle$$

such that

$$\mathcal{C} \times \mathcal{P} \models \varphi$$

Specification $\mapsto$ Controller

φ

$\mathcal{R}_\varphi$ D-Rabin

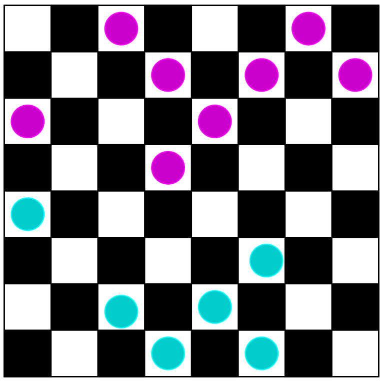
$\mathcal{P}$ Plant

$\mathcal{R}_\varphi \times \mathcal{P}$ Specification plant

[Thistle-Wonham 94]

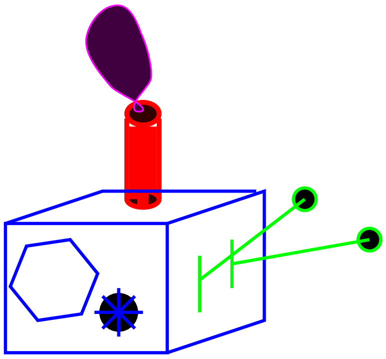
$\mathcal{C}$ Controller

Game $\mapsto$ Controller



$$\langle Q_0,\ Q_1,\ q_0,\ E_0,\ E_1,\ \Omega\rangle$$

$$\Big\Downarrow$$



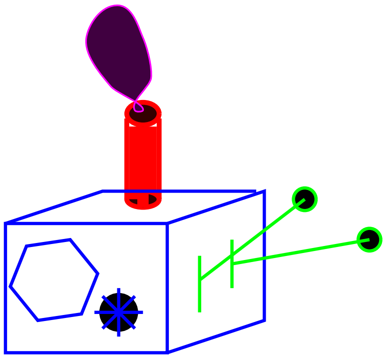
$$\langle Q,\ q_0,\ \Sigma,\ \delta,\ \Omega\rangle$$

$$Q = Q_0$$

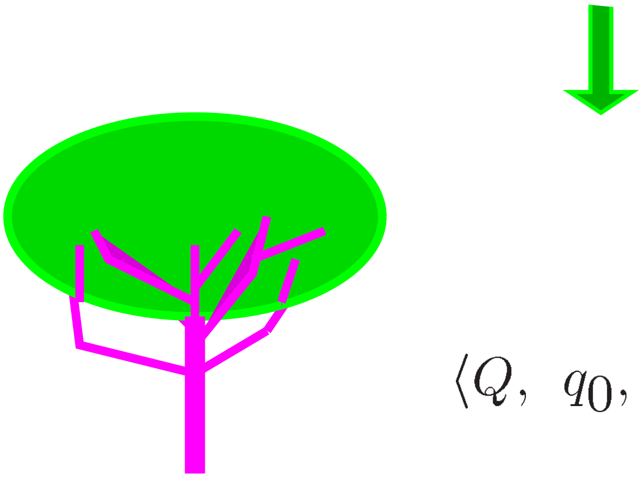
$$\Sigma = Q_1$$

$$\delta(q,a) = \{q' \in Q_0 \ :\ (q,a) \in E_0, (a,q') \in E_1\}$$

Controller $\mapsto$ Tree Automaton



$$\langle Q,\ q_0,\ \Sigma,\ \delta : Q \times \Sigma \to 2^Q,\ \Omega \rangle$$



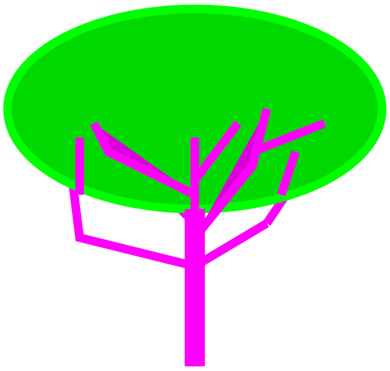
$$\langle Q,\ q_0,\ \Sigma,\ \delta_{\mathcal{T}} : Q \times \Sigma \to Q^*,\ \Omega \rangle$$

$$\delta(q,a) = \{q_0, \ldots, q_n\}$$

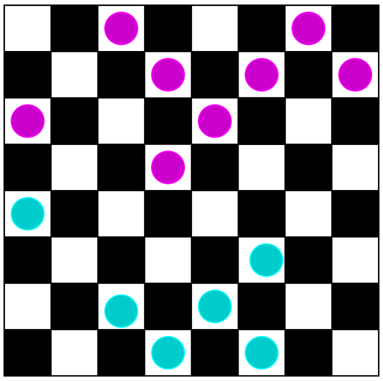
$$\Downarrow$$

$$\delta_{\mathcal{T}}(q,a) = \langle q_0, \ldots, q_n \rangle$$

Tree Automaton $\mapsto$ Game



$$\langle Q,\ q_0,\ \Sigma,\ \delta_{\mathcal{T}} : Q \times \Sigma \to Q^*,\ \Omega\rangle$$



$$\langle Q_0,\ Q_1,\ q_0,\ E_0,\ E_1,\ \Omega\rangle$$

$$Q_0 = Q$$

$$Q_1 = Q \times \Sigma$$

$$E_0 = \{(q, (q, a))\ :\ a \in \Sigma\}$$

$$E_1 = \{(((q, a), q')\ :\ \langle \ldots, q', \ldots\rangle = \delta_{\mathcal{T}}(q, a)\}$$

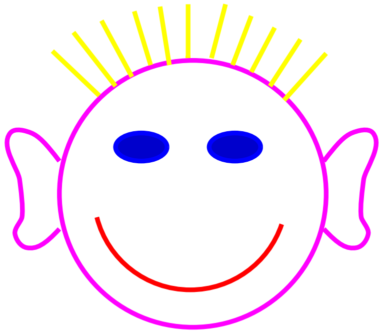
Complexity

	controller
Size of	transducer
	winning strategy

depends on acceptance condition

[Lescow 95 (CAV)] summarizes:

- Rabin - No memory needed
- Muller chain - Polynomial size
- Streett, Muller - Exponential size



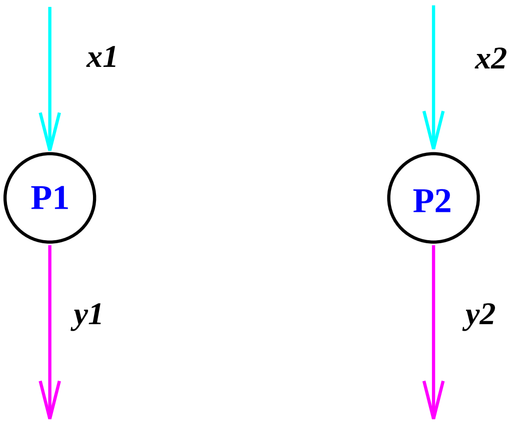
finite memory

Other Works on Complexity

[Rabin 69]	(LAR)
[Trakhtenbrot-Barzdin 70]	Monadic solvability
[Gurevich-Harrington 82]	LAR
[Klarlund 92]	Rabin-measures
[Nerode-Yakhnis-Yakhis 92]	Games
[Zeitman 94]	LAR
[Muller-Schupp 95]	IAR
[Krishnan-Puri-] [Brayton-Varaiya 95]	Rabin Index+ Chain automata
[Buhrke-Lescow-Vöge 96]	Streett+ Rabin chain

Multiprocessor synthesis

[Pnueli-Rosner 90]



- Hierarchical architectures

  NONELEMENTARY DECIDABLE

- Finite state

  UNDECIDABLE

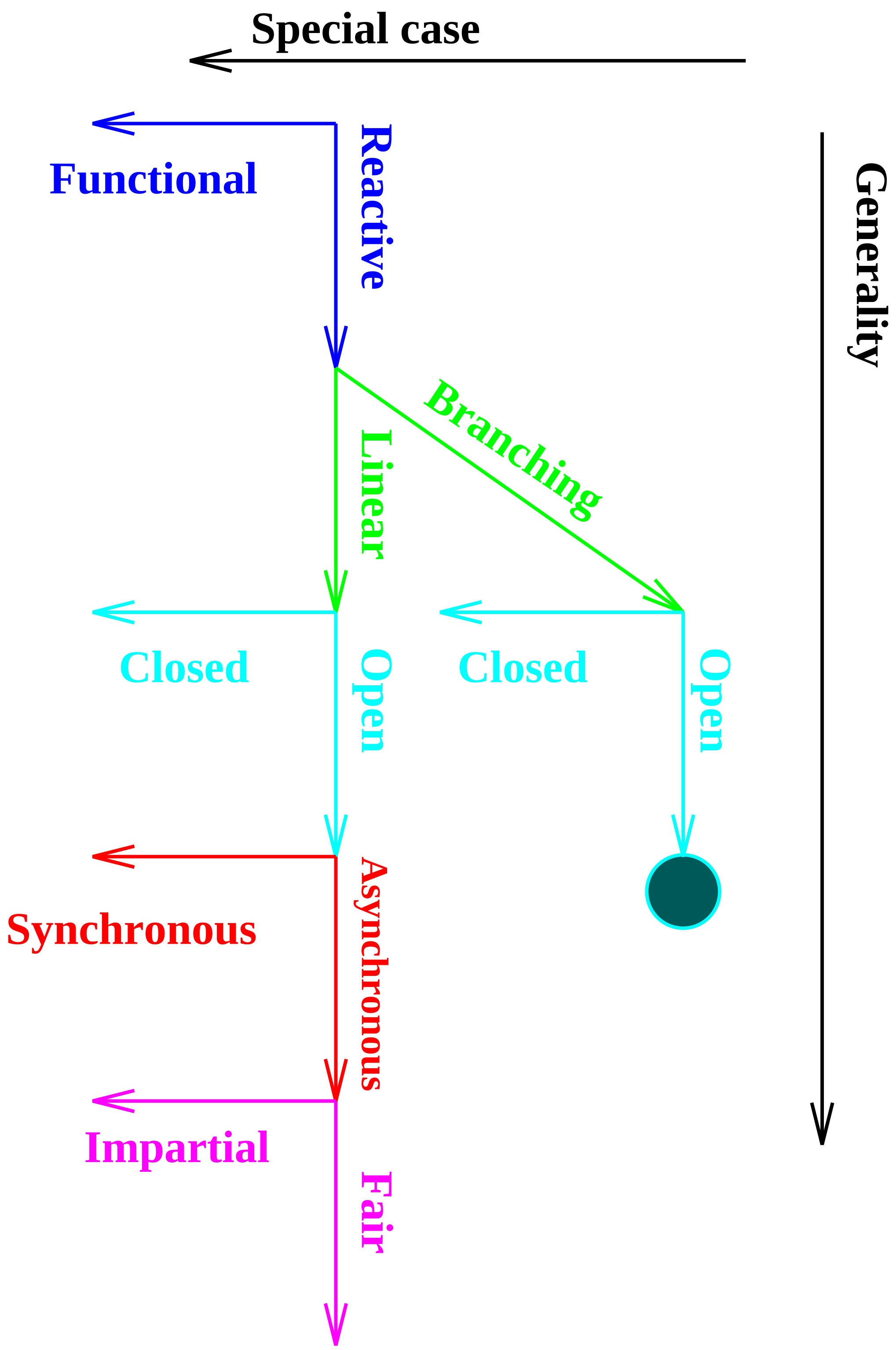
- Unrestricted

  HIGLY UNDECIDABLE

- Incomplete approach: Decomposition

  NONELEMENTARY DECIDABLE

Road Map



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Branches of the Church

Control plant to satisfy CTL specification.

State labeling CTL model-checking [Clarke-Emerson 81]

$\Downarrow$ adapted to

CTL control synthesis [Antoniotti 95,96]

Handles subset of CTL.

No memory allowed.

NP-complete for full CTL

Automata Theory for CTL

Tools developed for

- Alternating automata
  [Bernholtz 95] [Vardi 95]
- EQCTL
  [Kupferman 95]
- Module checking
  [Kupferman-Vardi 96 (CAV)]

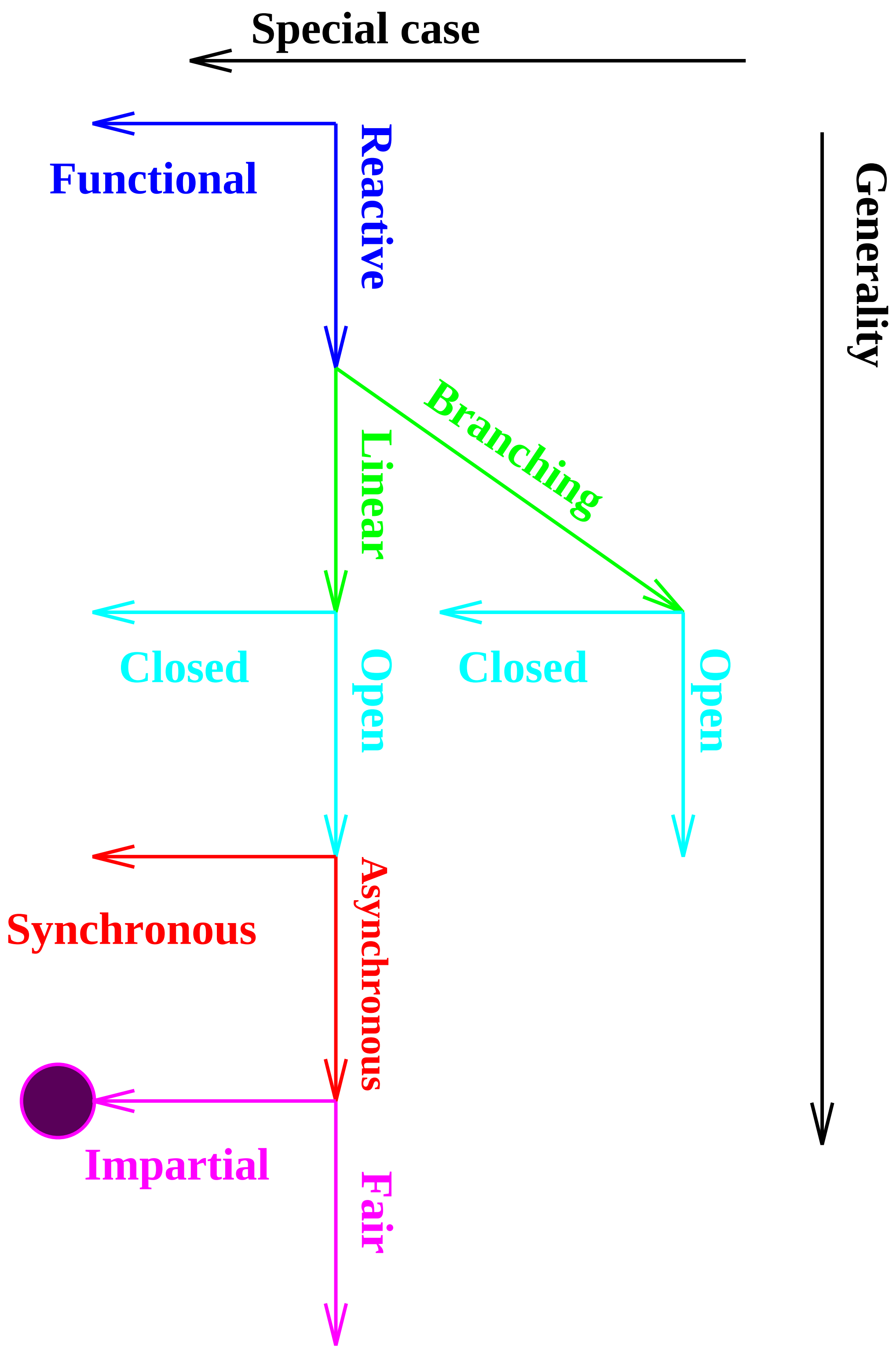
yield:

- CTL control (no memory allowed) is
  NP-complete
- CTL control (with memory) is
  EXPTIME complete
- CTL* control is
  2EXPTIME complete

Kupferman = Bernholtz

$\neg\Box(\text{Orna} = \text{Orna})$

Road Map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Asynchronous Synthesis

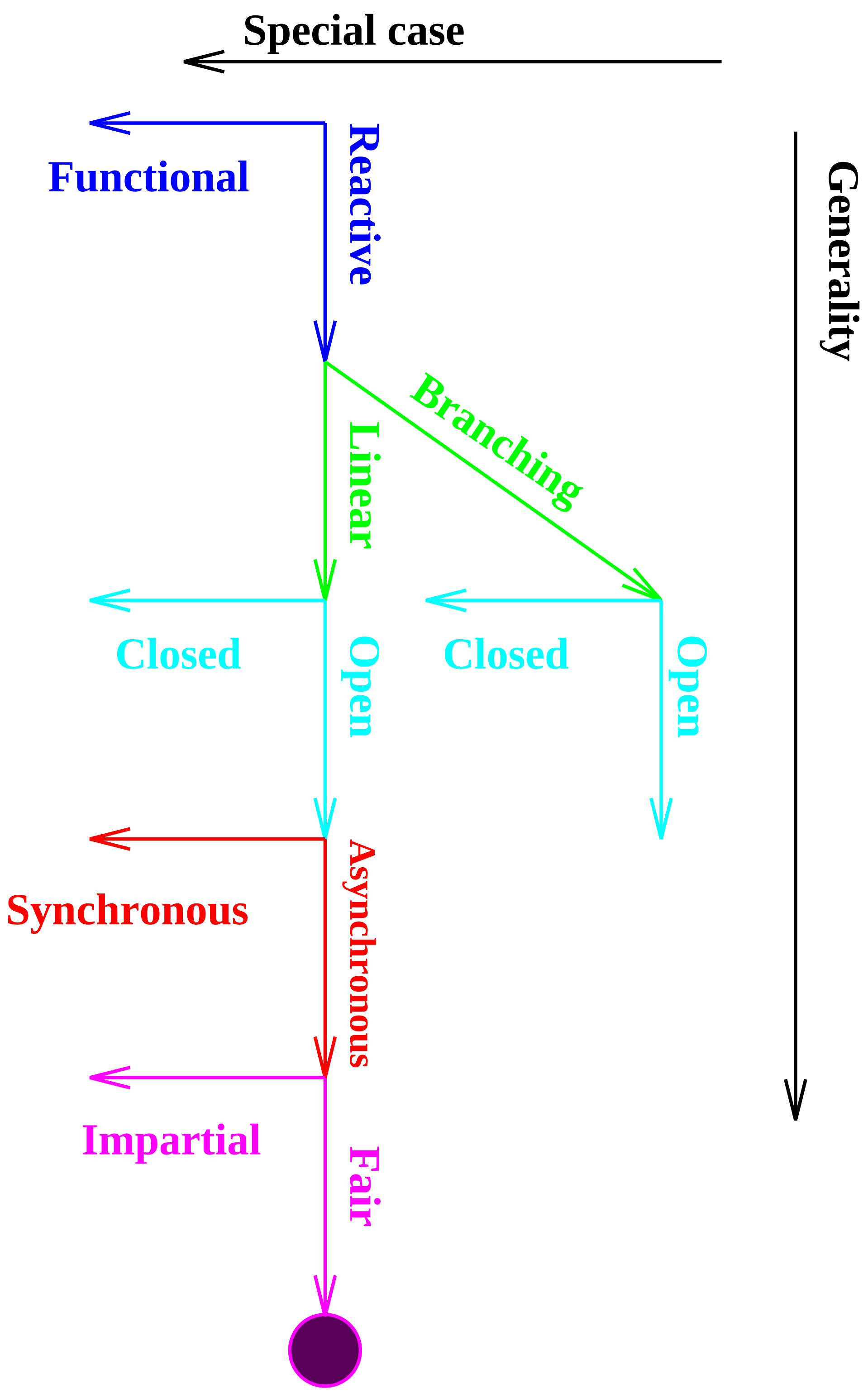
A third player: the scheduler.

- Environment and module interleave.
- Synthesized module only sees trace where it is scheduled.
- Scheduler is impartial: $\Box\Diamond$schedule.

[Pnueli-Rosner 89]
    Logical encoding
[Abadi-Lamport-Wolper 89]
    Failure traces
[Wong Toi-Dill 91]
    Flexible framework

2EXPTIME

Road Map



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Asynchronous Synthesis under Fairness

Scheduling under fairness assumptions:

- Just:

$$\Diamond \Box \text{Enabled} \rightarrow \Box \Diamond \text{schedule}$$

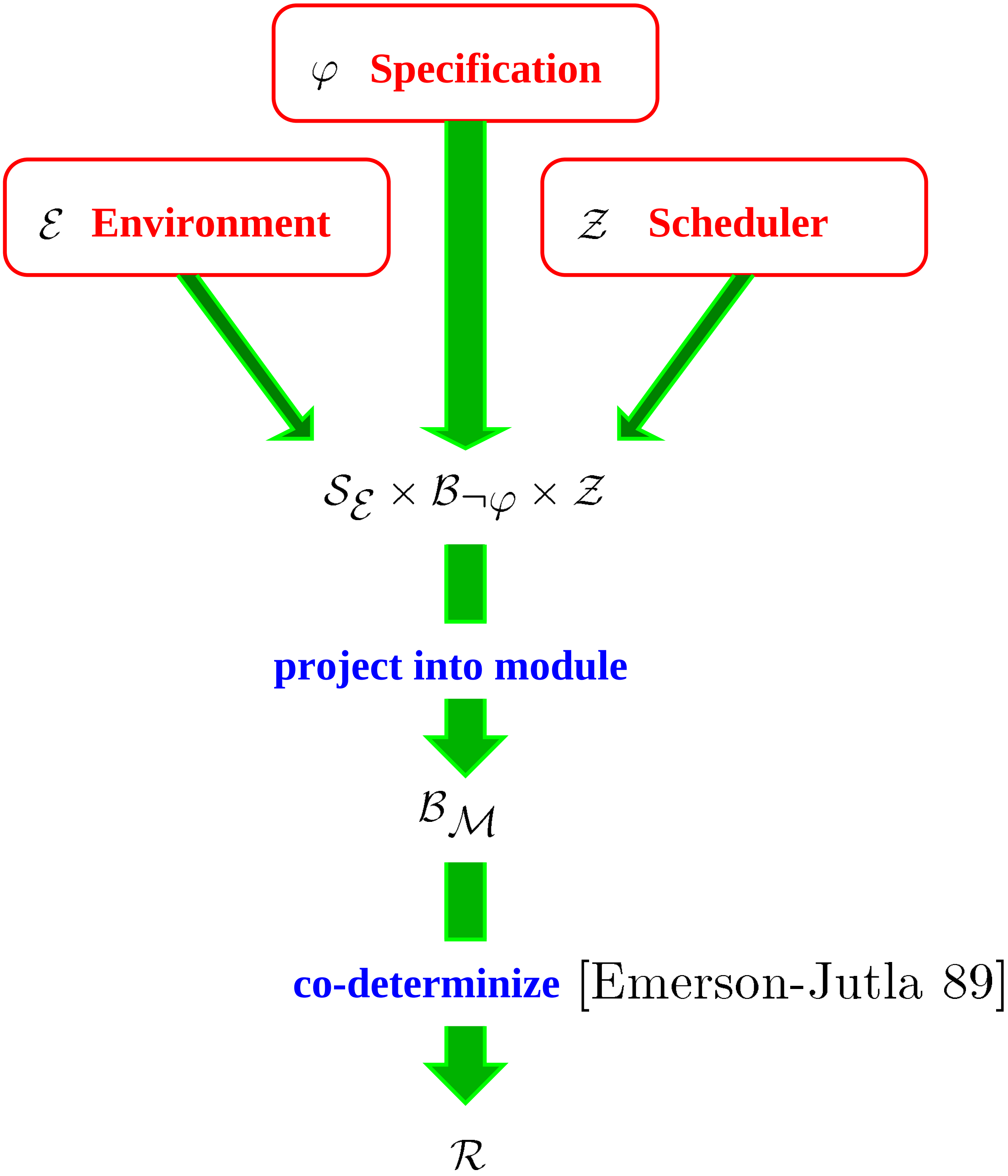
- Compassionate:

$$\Box \Diamond \text{Enabled} \rightarrow \Box \Diamond \text{schedule}$$

[Anuchitanukul-Manna 94]
Tableau based, ETL
[Vardi 95]
Automata based
2EXPTIME-complete in $\mathcal{B}$

3EXPTIME needed from LTL specification

General Modular Synthesis
[Anuchitanukul 95]



Real-time

Discrete control synthesis for real-time systems

[Wong Toi-Dill-Hoffmann 91,92]

Discretize region automata

[Maler-Pnueli-Sifakis-Asarin 95,96]

Controllable states from fixpoints

Real-time plant:

Σ	controllable actions
Q	system states
X	set of clocks
$F(X)$	reset functions on clocks
$I : Q \to \mathcal{H}_k^{\cap}$	state region invariants

$$R \quad \subseteq \quad Q \times \Sigma \times \mathcal{H}_k^{\cap} \times F(X) \times Q$$

Extract simple real-time controller:

$$C : Q \times X \to \Sigma \cup \{\text{clock}\}$$

Open Theoretical Problems

- Completing the branching time path
- Beyond $F_{\sigma\delta} \cap G_{\delta\sigma}$
  [Büchi 83]
- Games on pushdown automata
  [Thomas 95]
- More powerful real-time synthesis
  [Trachtenbrot 95]
- Synthesis for infinite state systems
- Proof-theoretical isomorphism for reactive synthesis
- Maximal synthesis for open systems
  [Anuchitanukul 95]

Open Practical Problems

From Toy examples
towards “Real” applications

Cats and mice
Mutual exclusion
[Ramadge-Wonham 89]
Semiconductor Manufacturing
[Wong Toi-Hoffmann 92]
Control of walking robot’s legs
Assembly line control
[Antoniotti 95]

Challenges

- More robots
- Highway control
- Flight control - a hybrid system
- Protocols in operating systems
- Bus protocols

References

Functional Synthesis work [BD77] [How80] [MW80] [Coq85] [CAB+86] [CH88] [HN88] [Smi90] [MT91] [Abr90]

Closed system synthesis [MW81] [CE81] [EC82] [MW84] [Anu95] [AE89]

Open synchronous [Chu62]

Trees [Rab72] [EJ88] [PR89b] [SVW87] [Saf88] [R.R92]

Games [GS53] [BL69] [McN93] [Les95, Tho95] [Dav64] [Mar75]

Control [RW89] [TW94a, TW94b] [MPS95] [OW90] [LW95]

Complexity [Les95] [Rab69] [GH82] [PR90] [Kla92] [NYY92] [YY93] [TL93] [KK91] [Tho94] [Zei94] [MS95] [KPBV95] [BLV96]

Branching [Ant95] [Kup95b] [Kup95a] [KV96] [Var96]

Asynchronous [PR89a] [ALW89] [DW91]

Fair [AM94] [Var95]

Real time [WH92] [MPS95] [AMP96]

Various [Büc83] [EJ88] [EJ89, EJ91] [EH93]

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