From Offline Long-Run to Online Short-Run: Exploring A New Approach of Hybrid Systems Model Checking for MDPnP

Tao Li*, Qixin Wang*, Feng Tan*, Lei Bu, Jian-nong Cao*,
Xue Liu, Yufei Wang*, Rong Zheng

*The Hong Kong Polytechnic Univ.

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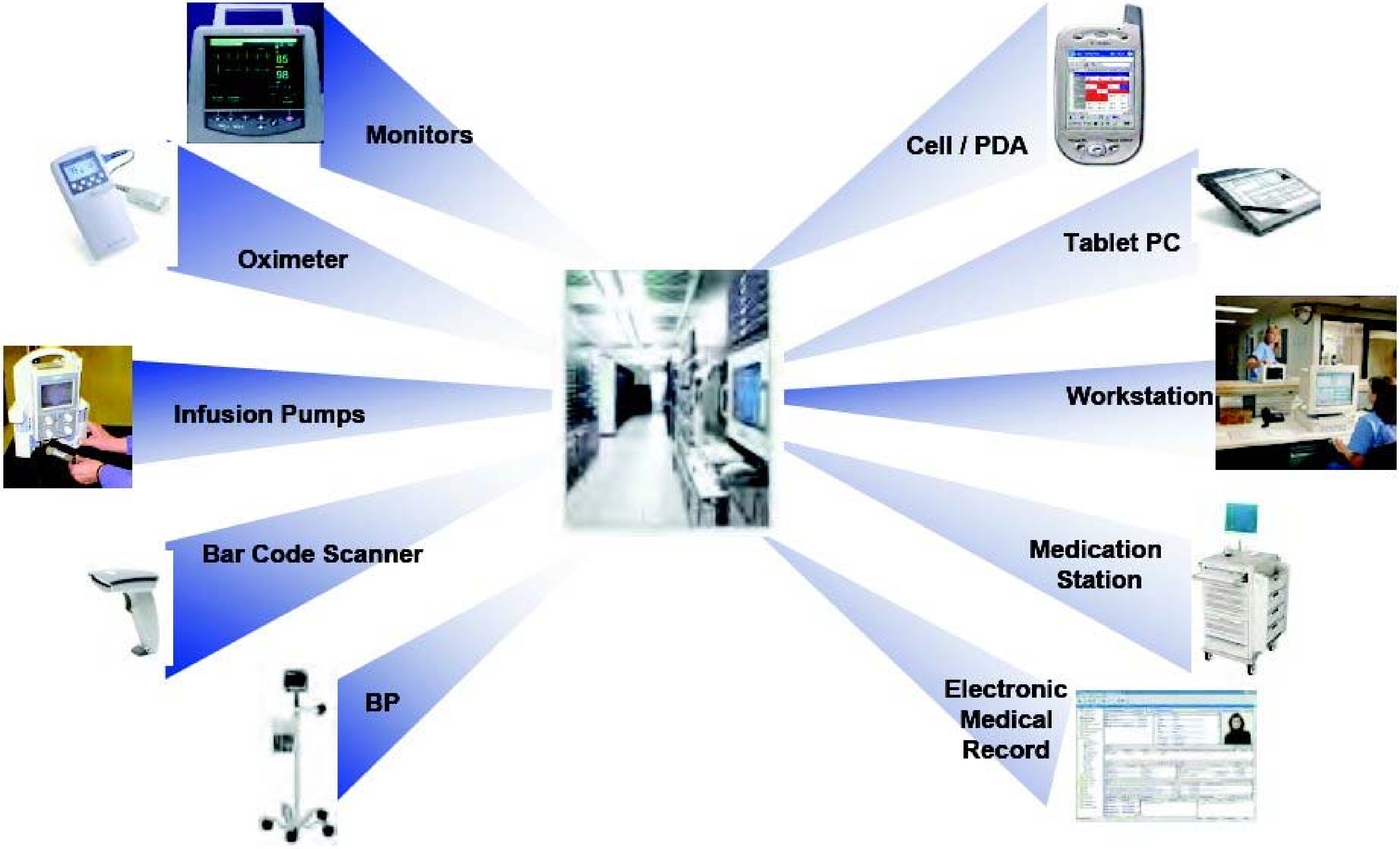
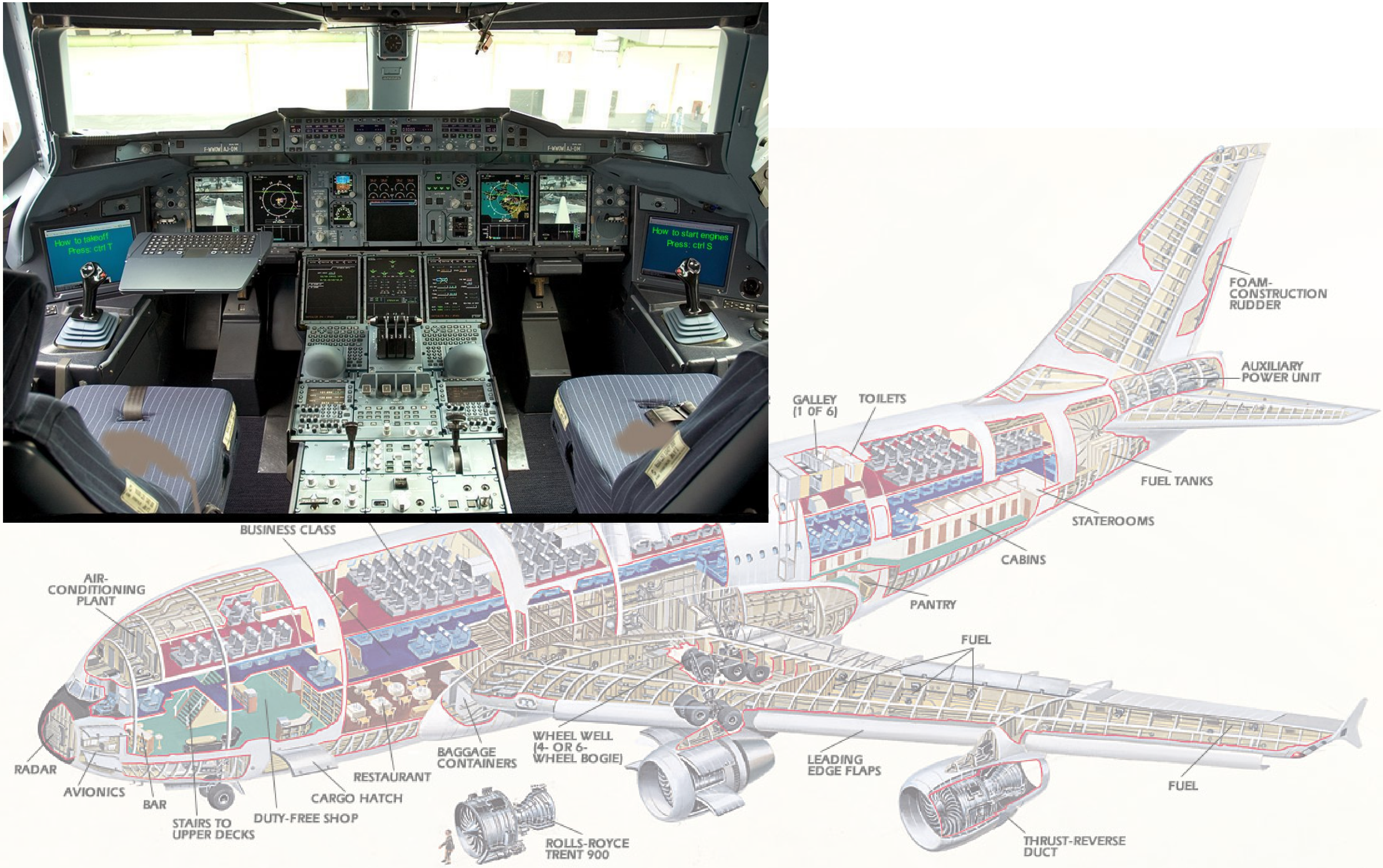
MDPnP leads to better safety, capability, and convenience of medical settings.



MDPnP can help prevent many serious/lethal accidents in medical settings.

Following the success of requiring avionics to be verifiably safe → MDPnP to be verifiably safe.



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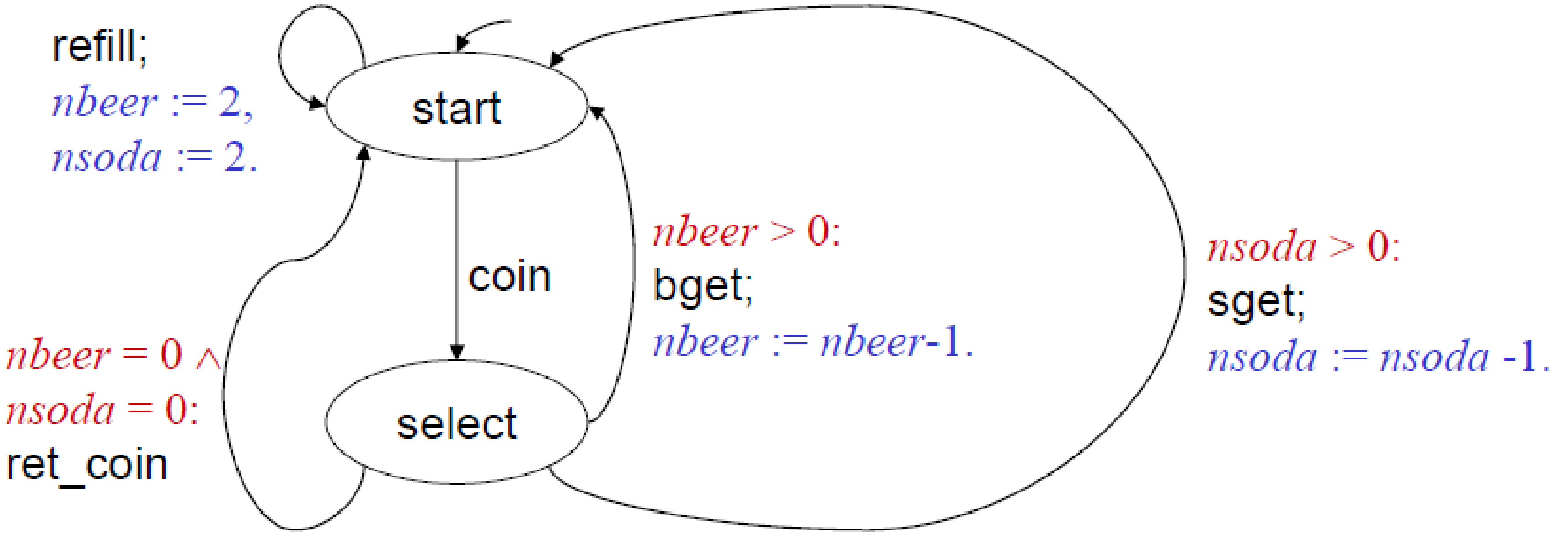
A key tool for traditional computer systems verification is model checking.



refill;
$nbeer := 2,$
$nsoda := 2.$

start

coin

select

$nbeer > 0:$
bget;
$nbeer := nbeer\text{-}1.$

$nsoda > 0:$
sget;
$nsoda := nsoda\ \text{-}1.$

$nbeer = 0 \wedge$
$nsoda = 0:$
ret_coin

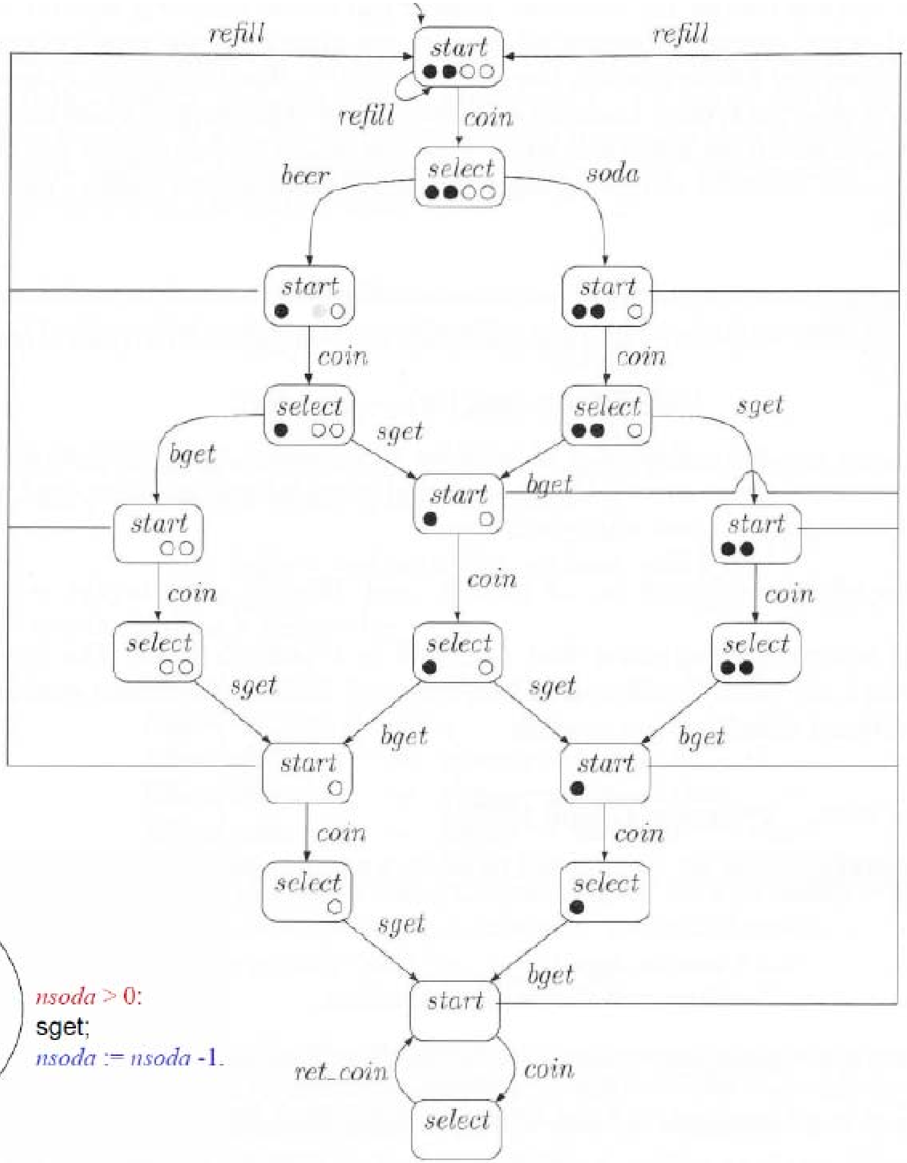
$Var = \{nbeer, nsoda\}$, $\text{domain}(nbeer) = \{0, 1, 2\}$, $\text{domain}(nsoda) = \{0, 1, 2\}$

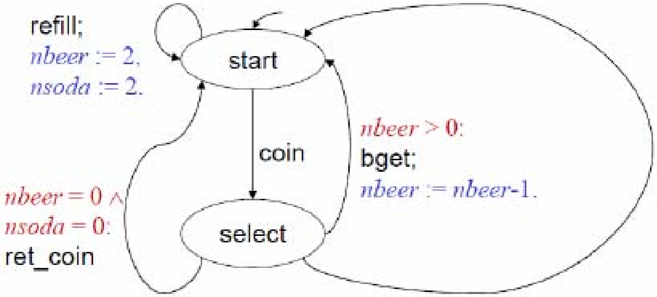
$$PG = (Loc, Act, Effect, :\rightarrow, Loc_0, g_0)$$

Computer systems model checking verifies safety, liveliness, persistence, and other properties.

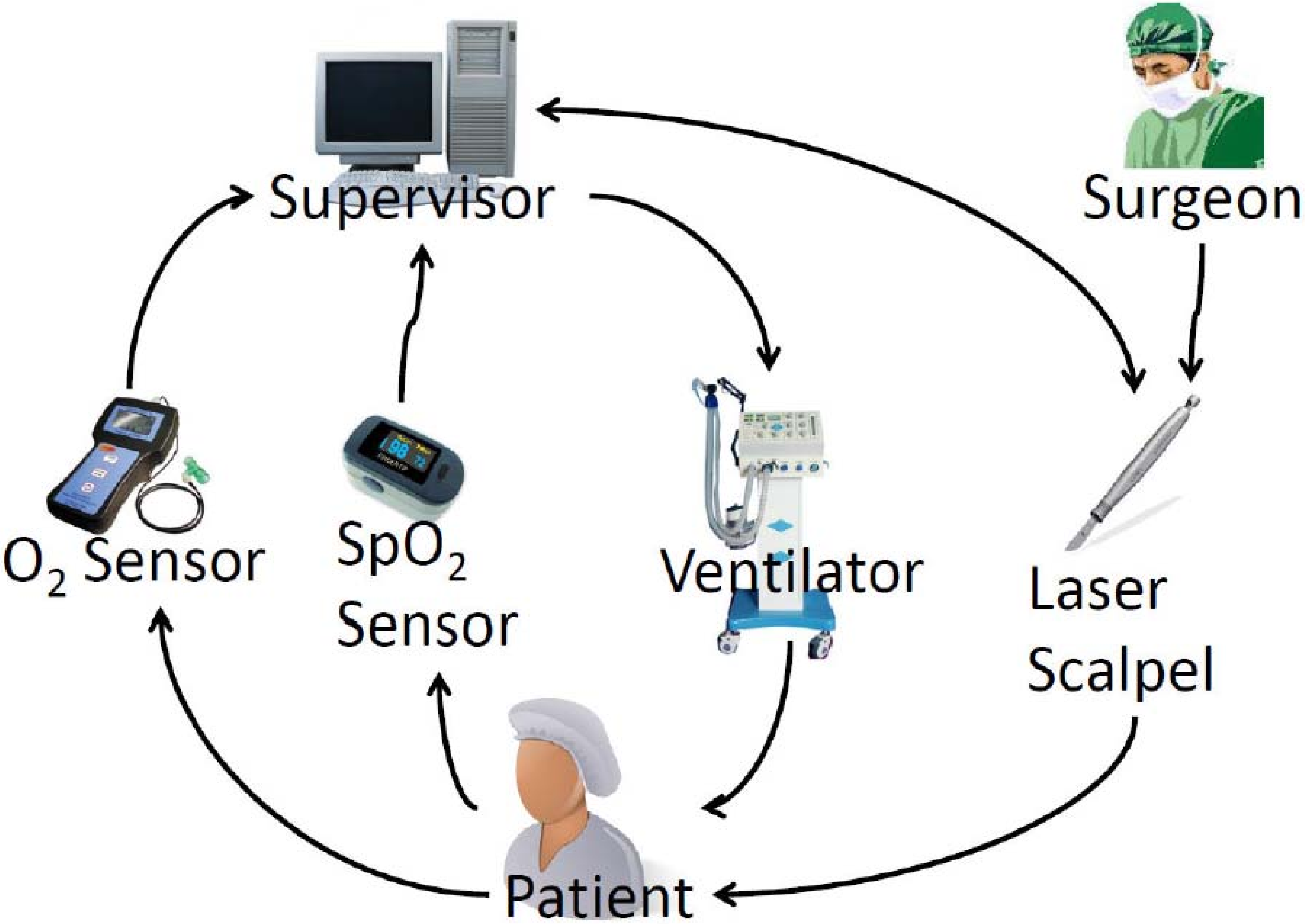
Transition System of a Program Graph Example

Note the combinatorial explosion of size.





MDPnP is not just a computer system, it is a hybrid of computer & other systems, i.e., CPS.



Laser Tracheotomy MDPnP

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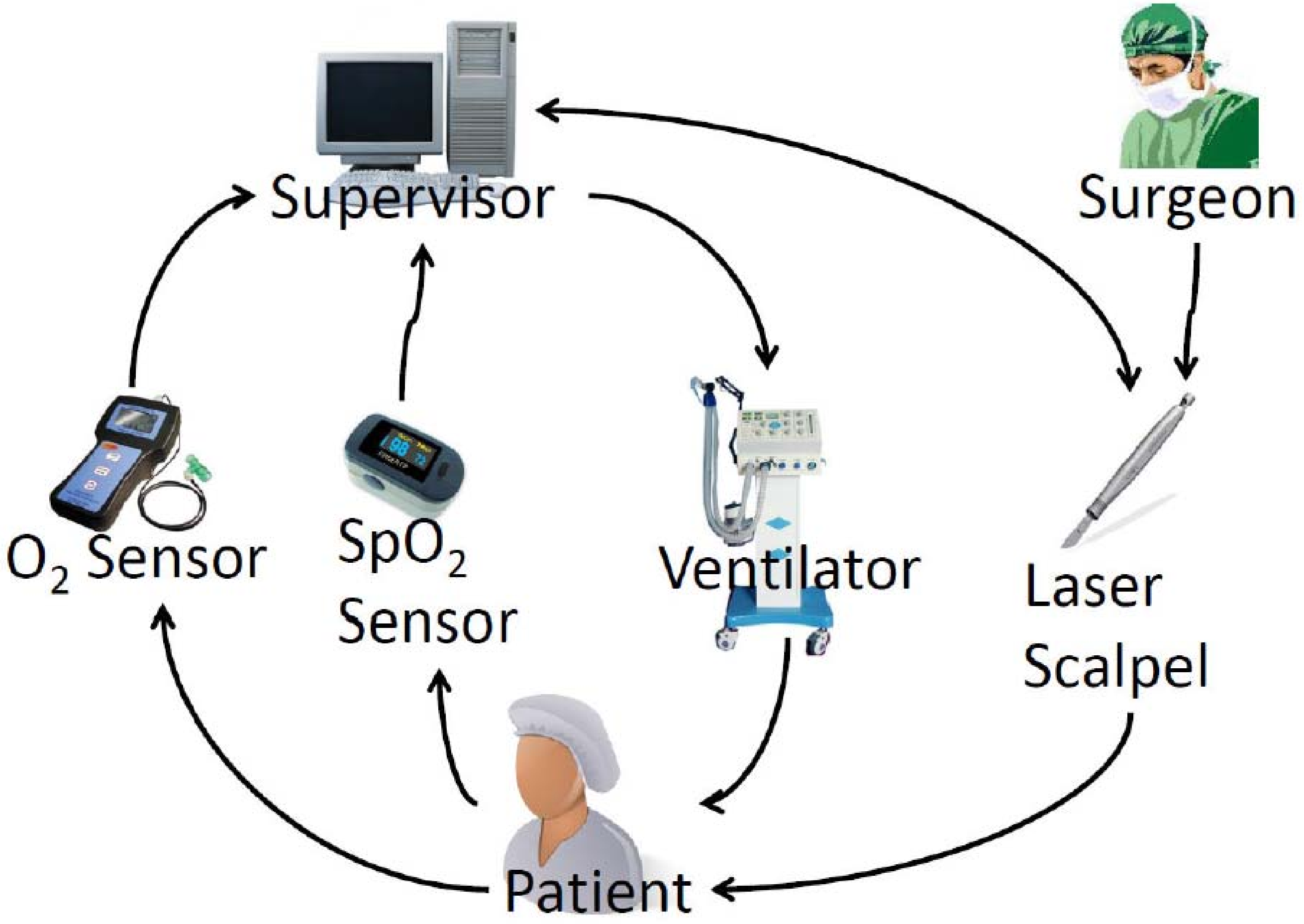
Computer



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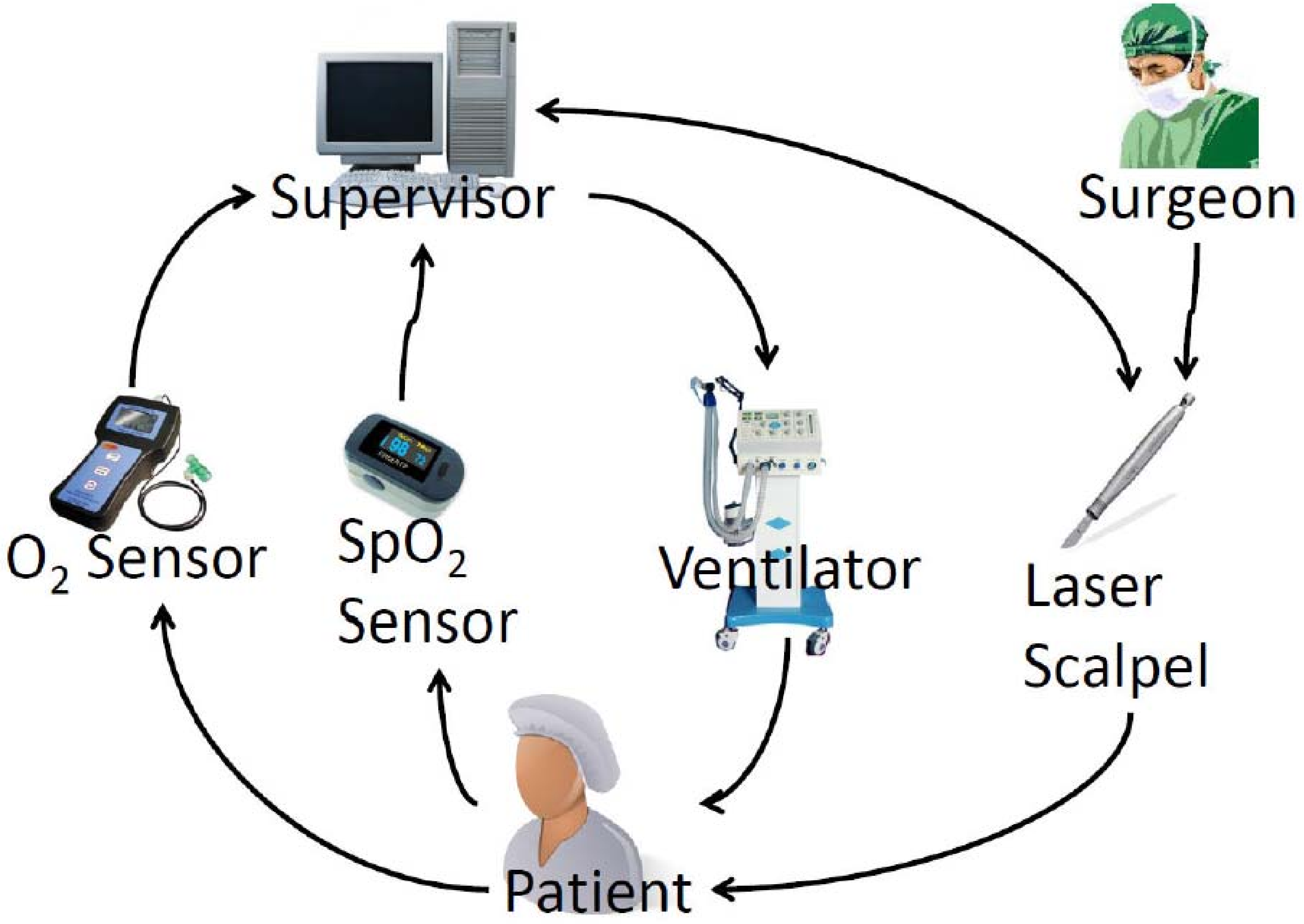
Biochemical



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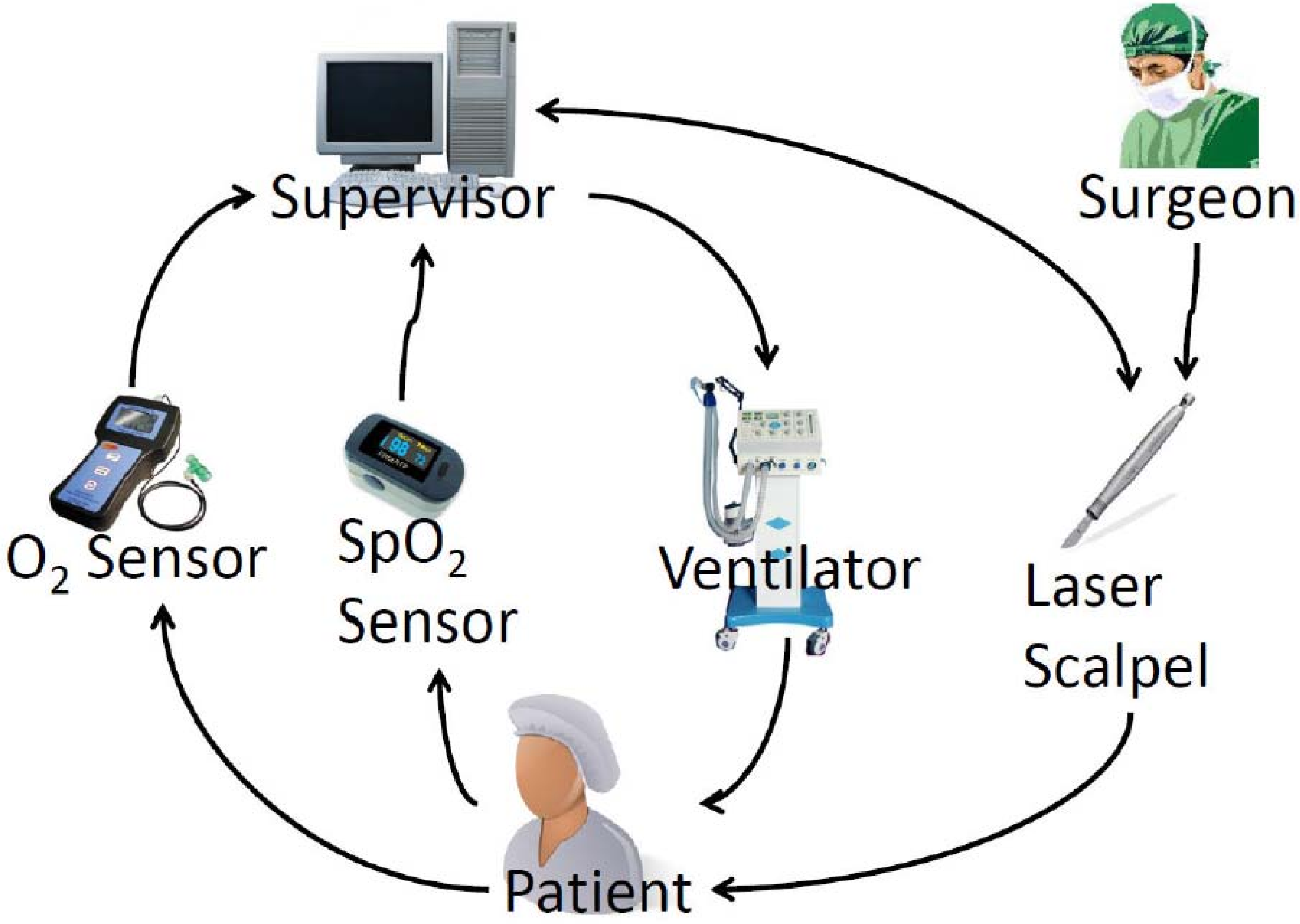
Biochemical

Mechanical



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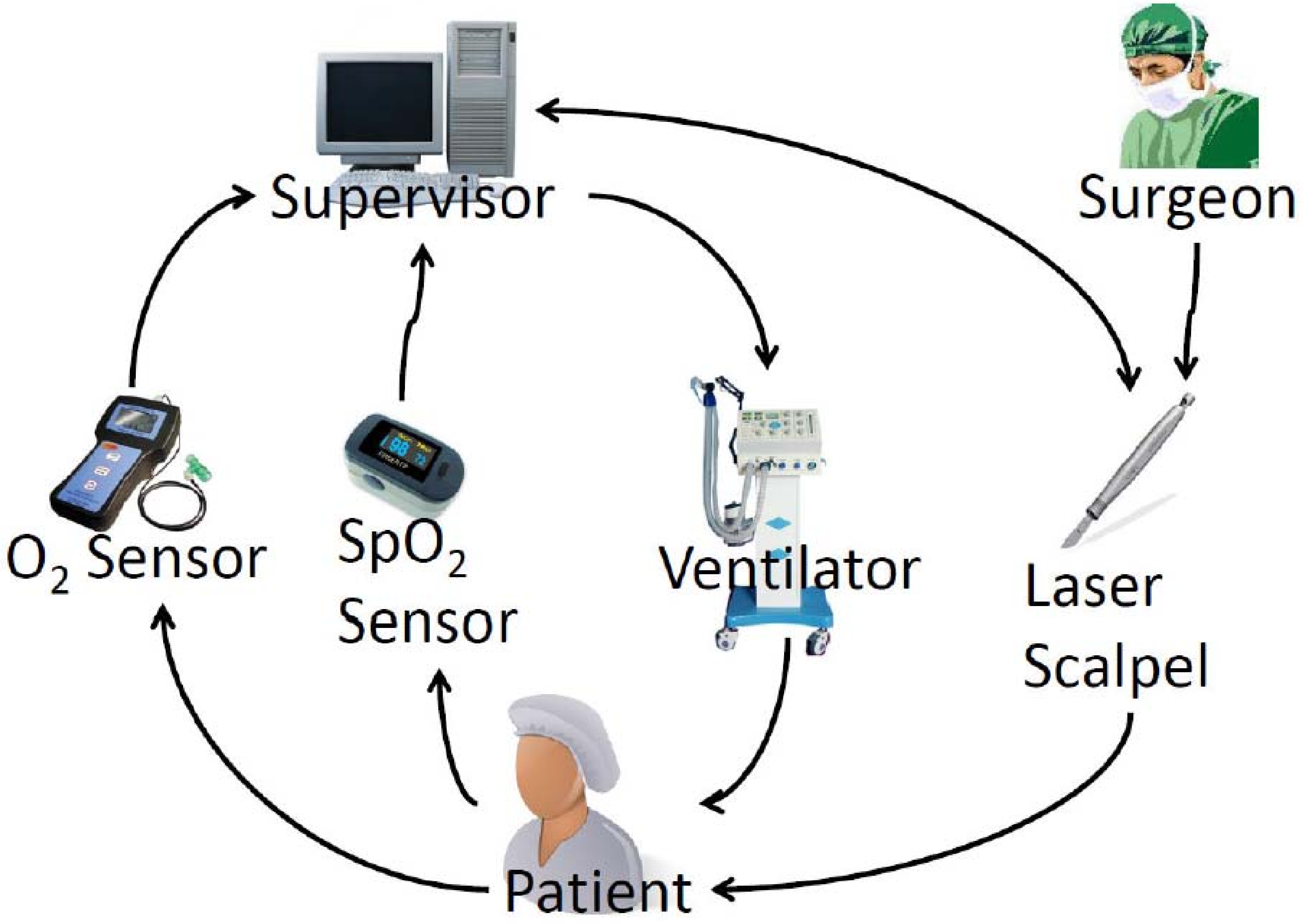
Computer

Biochemical

Mechanical

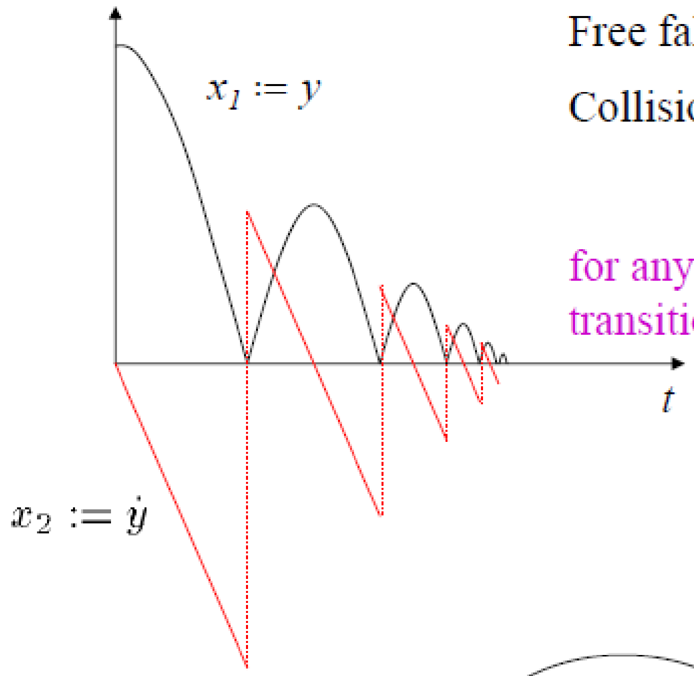
Communication



Laser Tracheotomy MDPnP

A state-of-the-art CPS model checking is Hybrid Systems Model Checking: Comp + Fdbk Ctrl.

Bouncing Ball Example



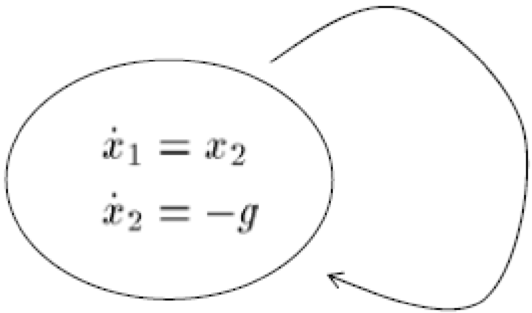
Free fall $\equiv \quad \ddot{y} = -g$

$$\text{Collision} \equiv \quad \begin{aligned} y^+(t) &= y^-(t) = 0 \\ \dot{y}^+(t) &= -c\dot{y}^-(t) \end{aligned}$$

for any c < 1, there are infinitely many transitions in finite time (Zeno phenomena)

guard or jump condition

$x_1 = 0$ & $x_2 < 0$?



$$\dot{x}_1 = x_2$$
$$\dot{x}_2 = -g$$

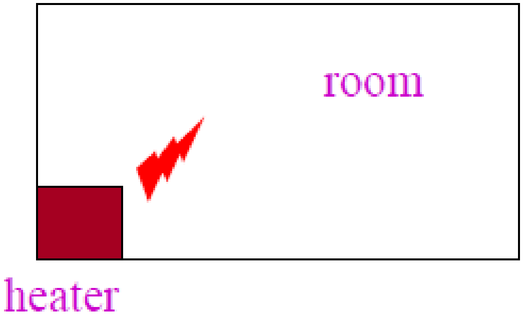
transition

$X_2 := - \; c \; X_2^-$

state reset

The state-of-the-art CPS model checking is Hybrid Systems Model Checking: Comp + Fdbk Ctrl.

Thermostat Example



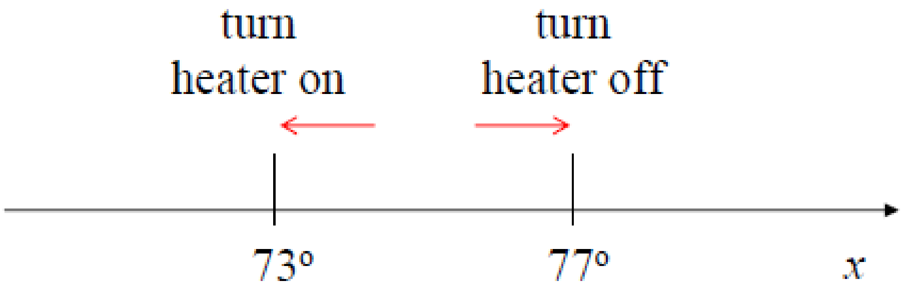
goal ≡ regulate temperature around 75°

$x \equiv$ mean temperature

when heater is off: $\dot{x} \approx -x + 50$ $(x \to 50^\circ)$

when heater is on: $\dot{x} \approx -x + 100$ $(x \to 100^\circ)$

event-based control



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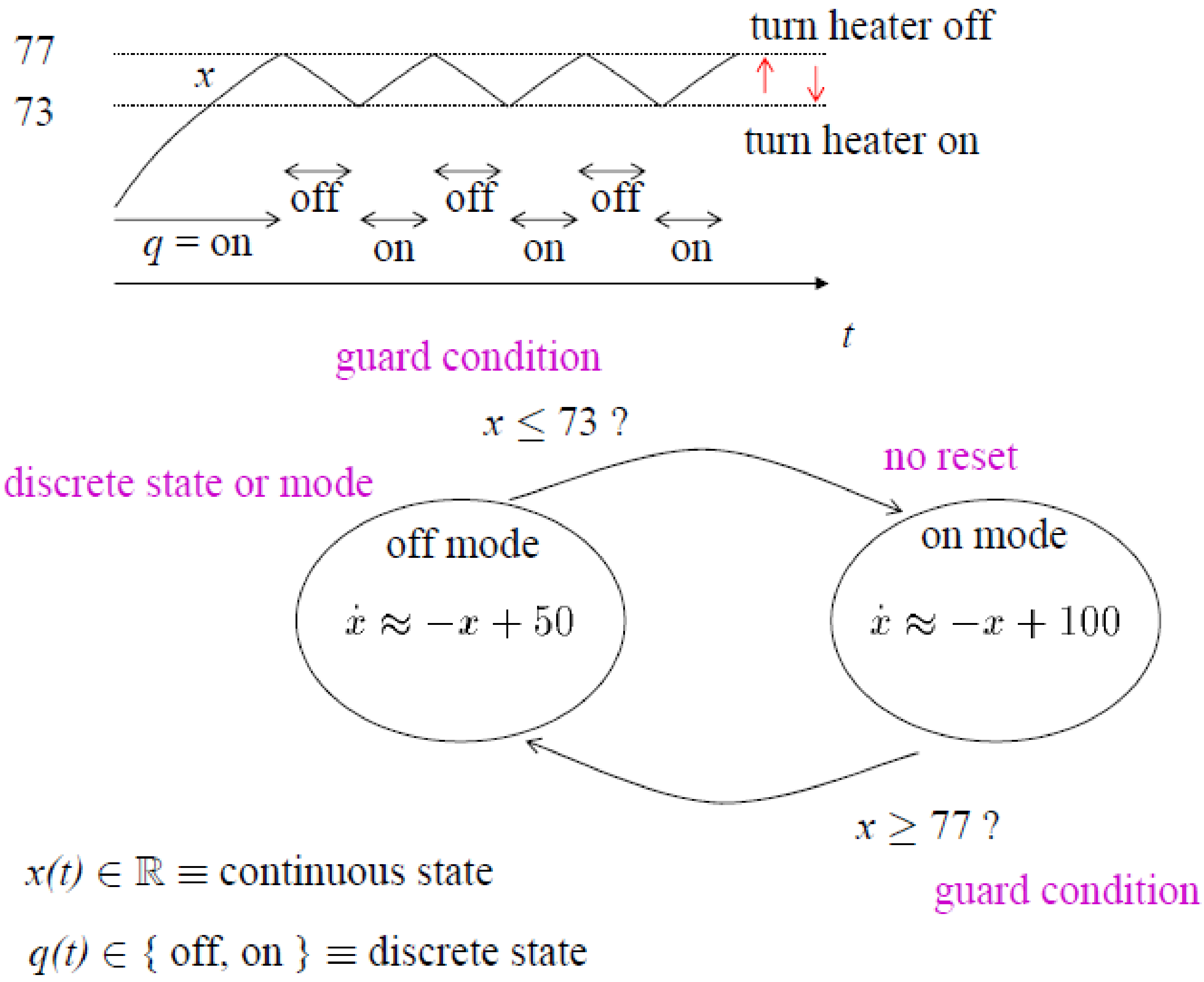

$x(t) \in \mathbb{R} \equiv$ continuous state

$q(t) \in \{$ off, on $\} \equiv$ discrete state

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However, existing hybrid systems model checking (computer + fdbk ctrl) doesn’t very well fit MDPnP.

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Existing model checking:

Offline (partly due to lack of time cost bound),

Time-Unbounded Behavior (Long-Run Future)

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Challenge 1: No good offline models for complex biomedical systems of human body.

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Existing model checking:

Offline (partly due to lack of time cost bound),

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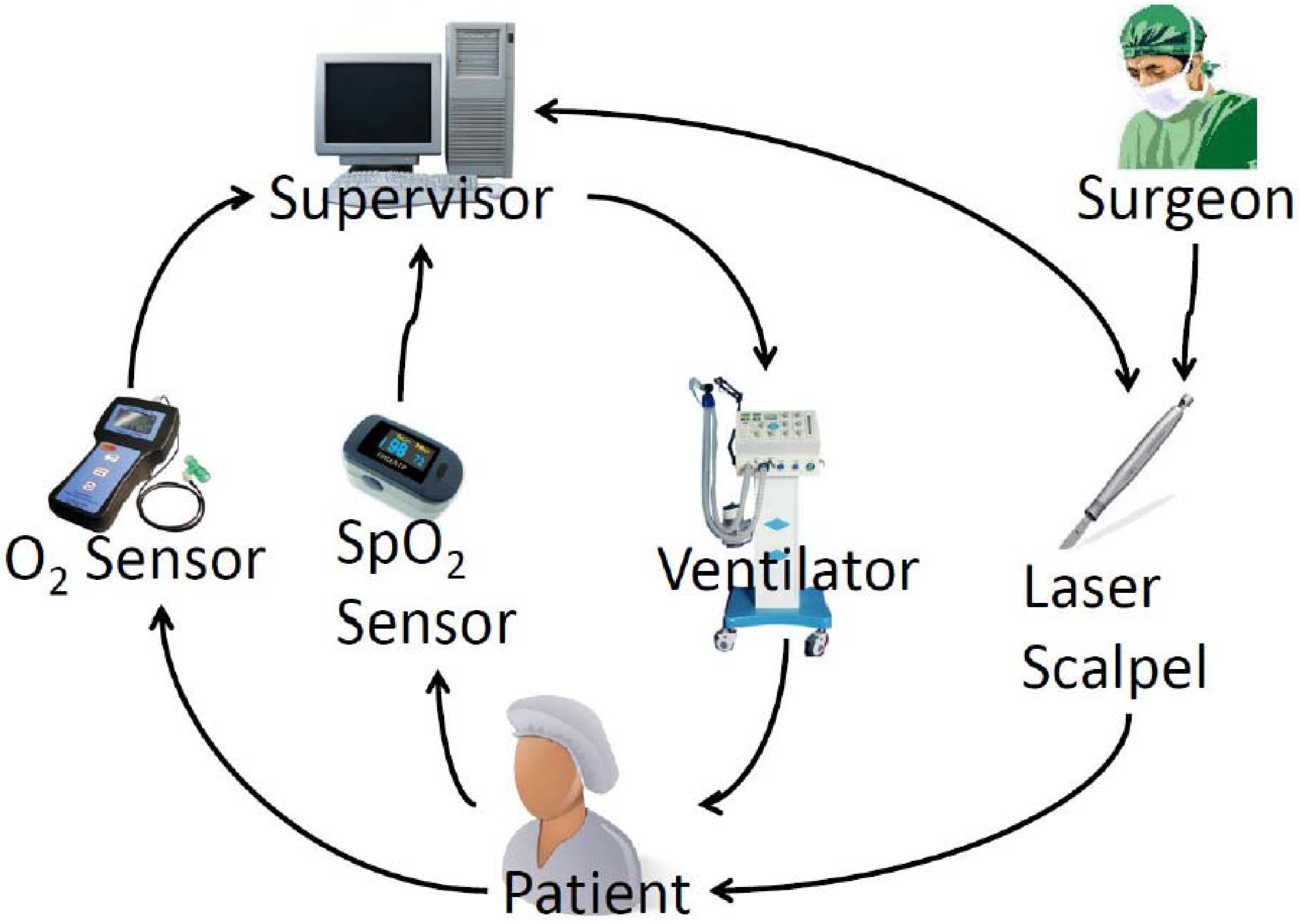
Challenge 2: Verification state space easily explode.

Take laser tracheotomy offline hybrid systems modeling as an example.



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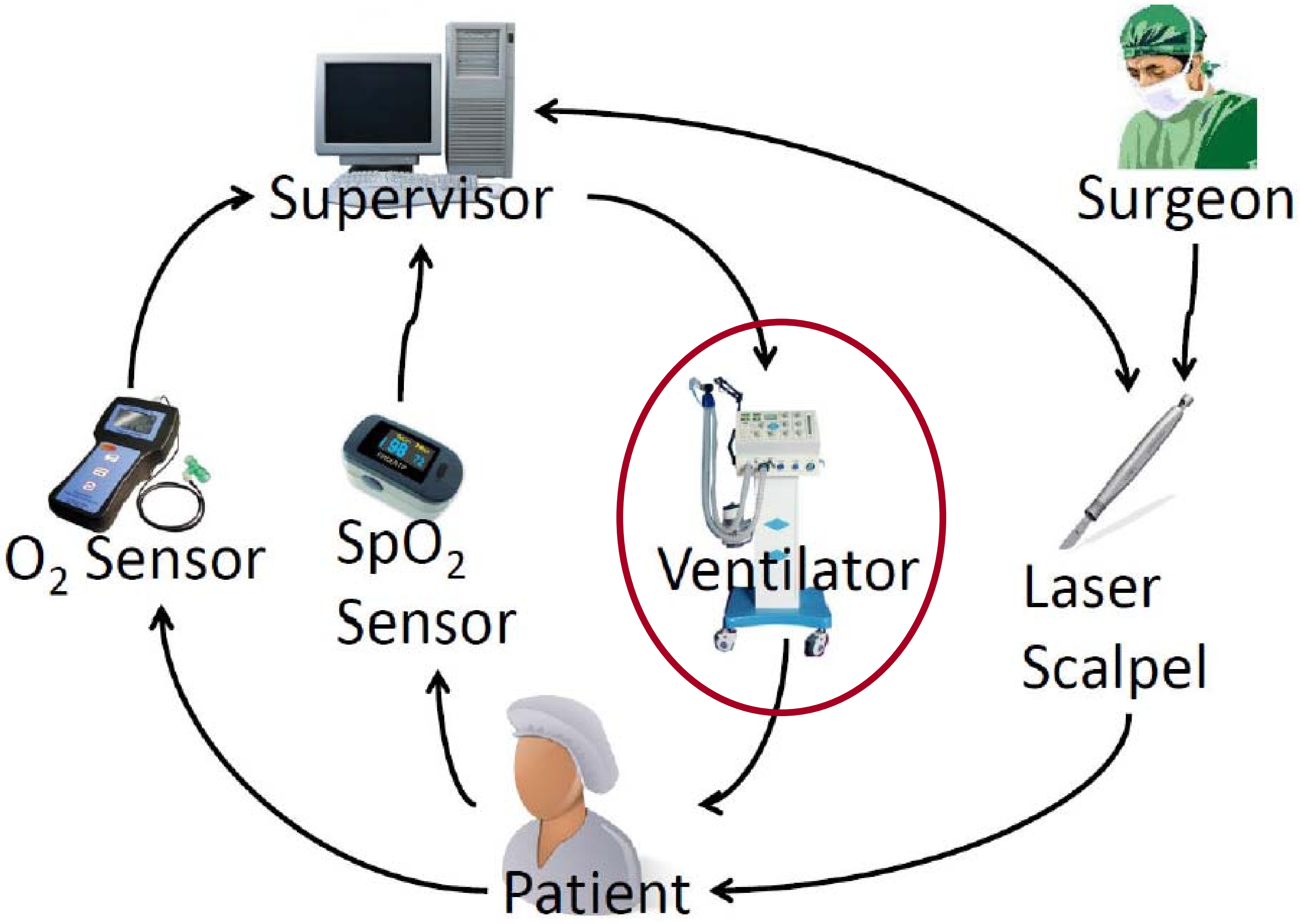

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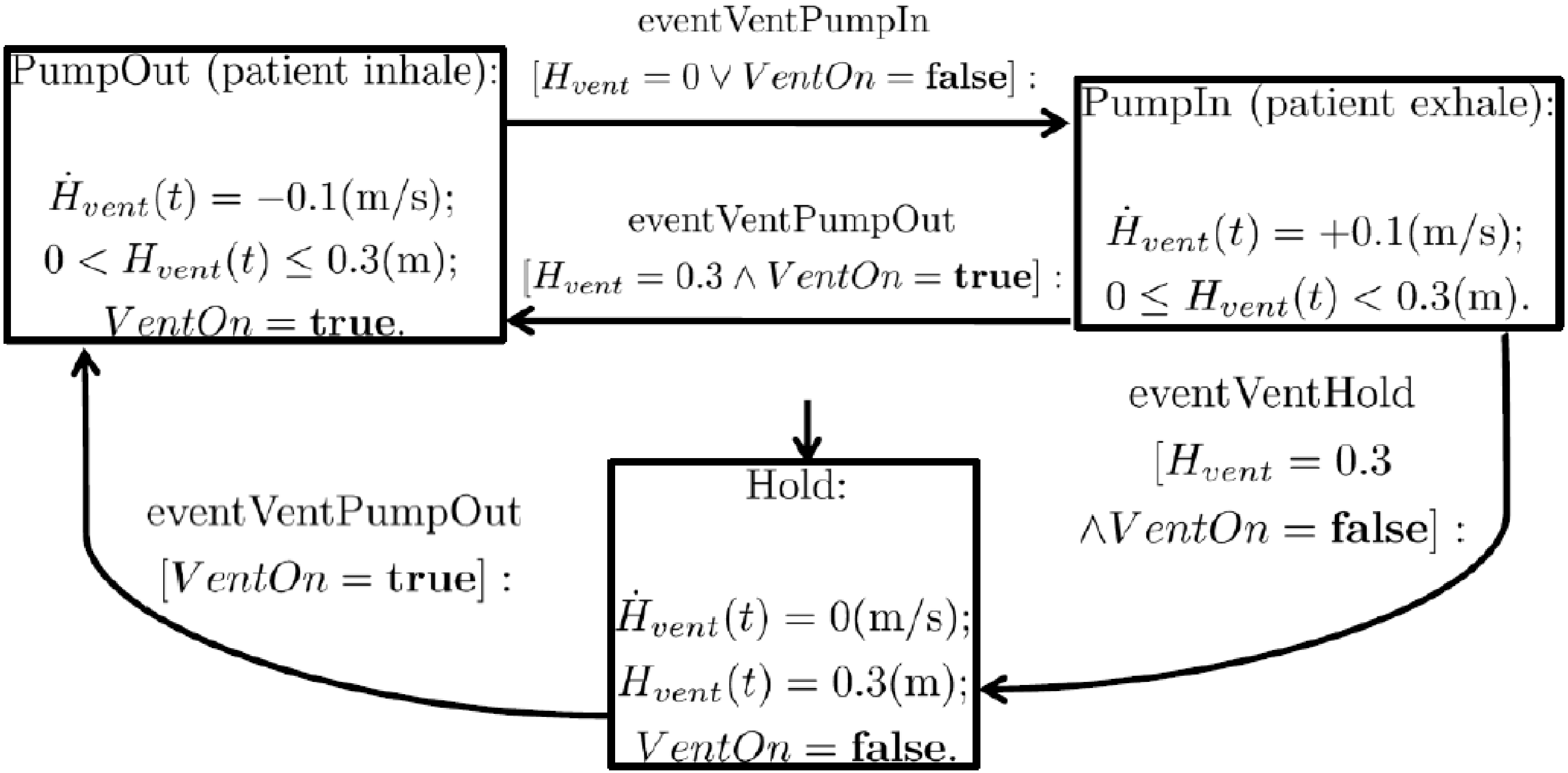

PumpOut (patient inhale):

$\dot{H}_{vent}(t) = -0.1(\mathrm{m/s})$;

$0 < H_{vent}(t) \leq 0.3(\mathrm{m})$;

$VentOn = \textbf{true}$.

eventVentPumpIn

$[H_{vent} = 0 \vee VentOn = \textbf{false}]$:

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eventVentPumpOut

$[H_{vent} = 0.3 \wedge VentOn = \textbf{true}]$:

eventVentHold

$[H_{vent} = 0.3$

$\wedge VentOn = \textbf{false}]$:

Hold:

$\dot{H}_{vent}(t) = 0(\mathrm{m/s})$;

$H_{vent}(t) = 0.3(\mathrm{m})$;

$VentOn = \textbf{false}$.

eventVentPumpOut

$[VentOn = \textbf{true}]$:

Legend:

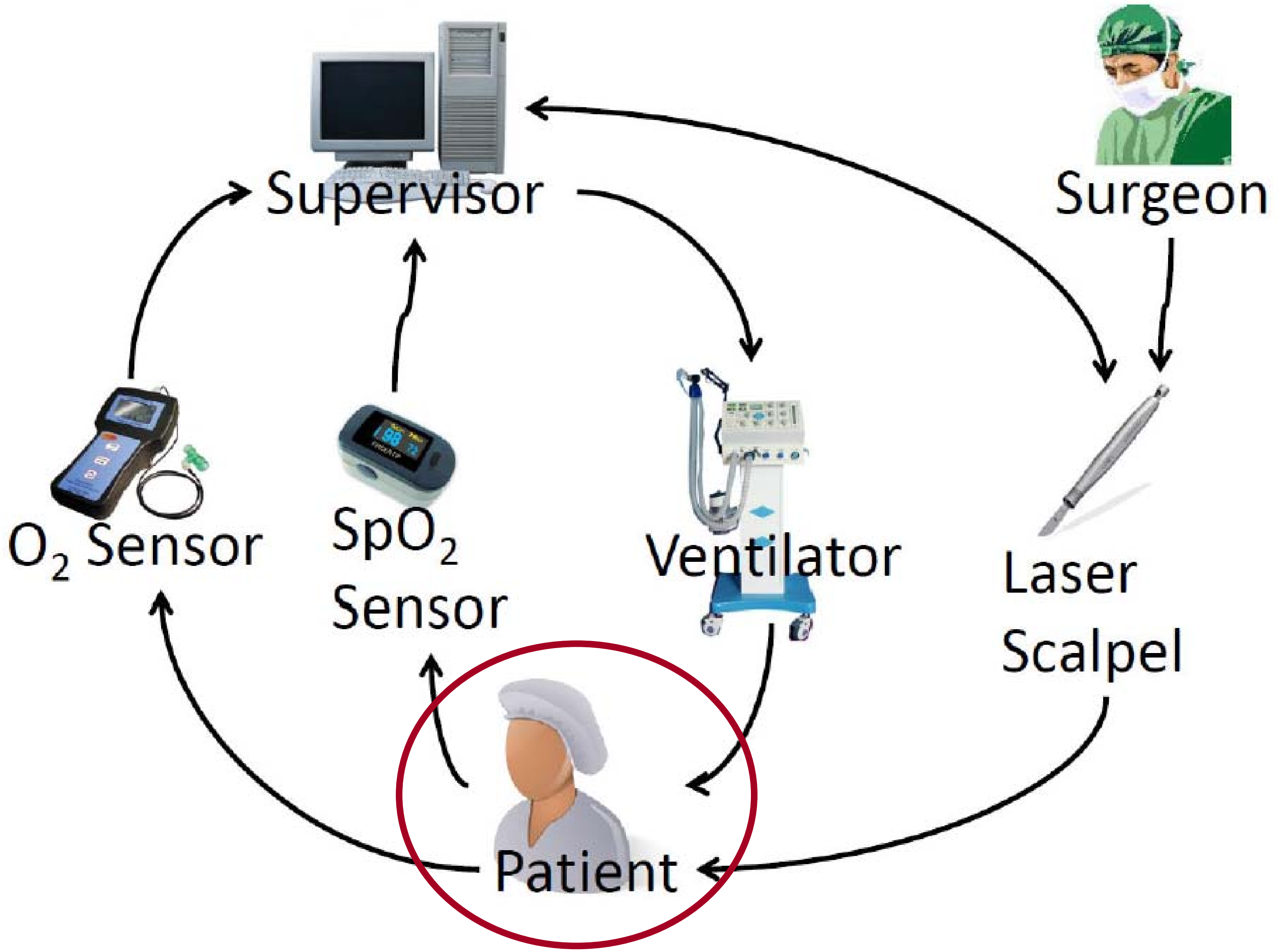
→ (w/ source location) Event; (w/o source location) Initial location indicator

□ Location

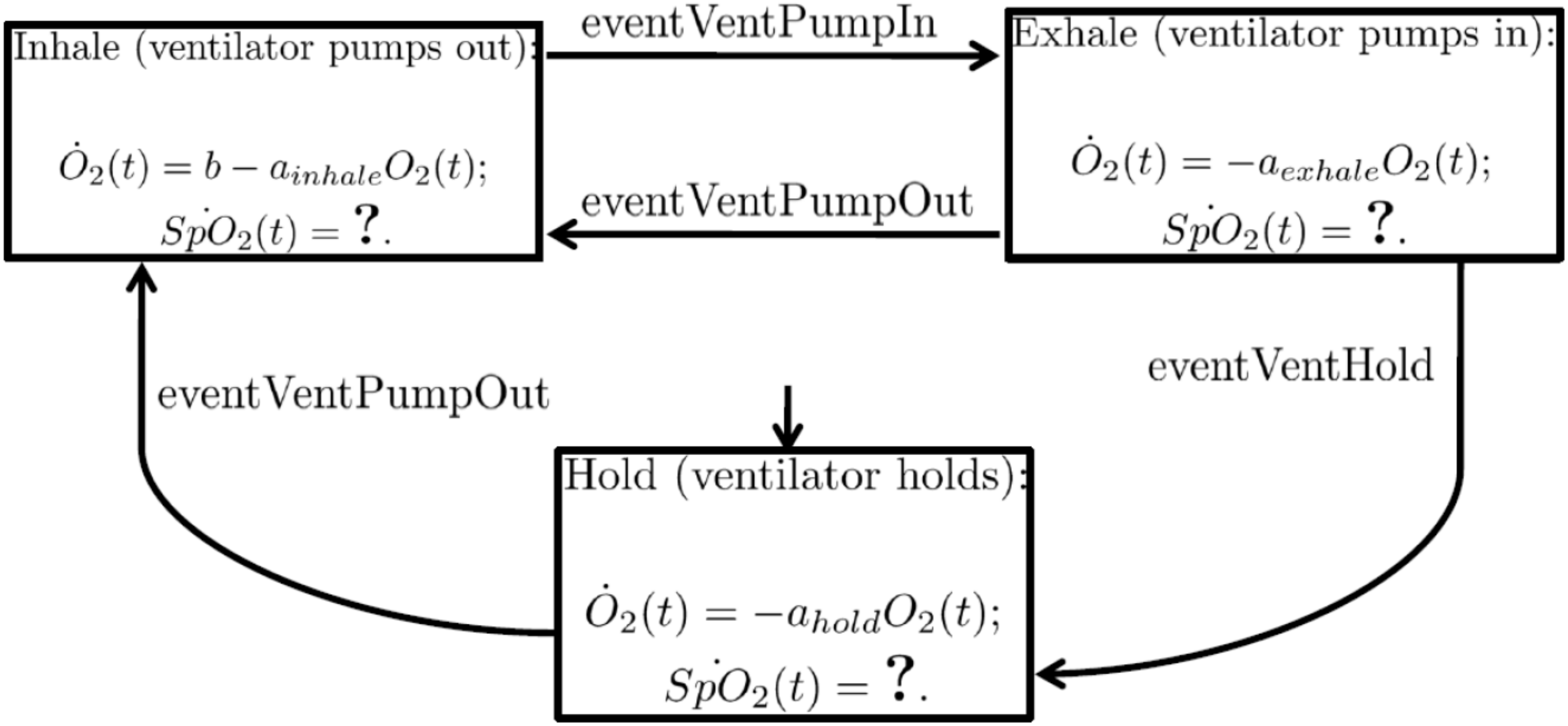
[ ] Event guard (event triggering condition)

:= Variable value update

Take laser tracheotomy offline hybrid systems modeling as an example.



Take laser tracheotomy offline hybrid systems modeling as an example: model SpO_2 offline?



Inhale (ventilator pumps out):
$\dot{O}_2(t) = b - a_{inhale}O_2(t);$
$S\dot{p}O_2(t) = ?.$
eventVentPumpIn
Exhale (ventilator pumps in):
$\dot{O}_2(t) = -a_{exhale}O_2(t);$
$S\dot{p}O_2(t) = ?.$
eventVentPumpOut
eventVentHold
eventVentPumpOut
Hold (ventilator holds):
$\dot{O}_2(t) = -a_{hold}O_2(t);$
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Online periodical real-time hybrid systems model checking of time-bounded (i.e., short-run) future!

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Traditional model checking vs. Ours:

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Most vital signs' online short-run behavior is easy to predict.

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Most vital signs' online short-run behavior is easy to predict.

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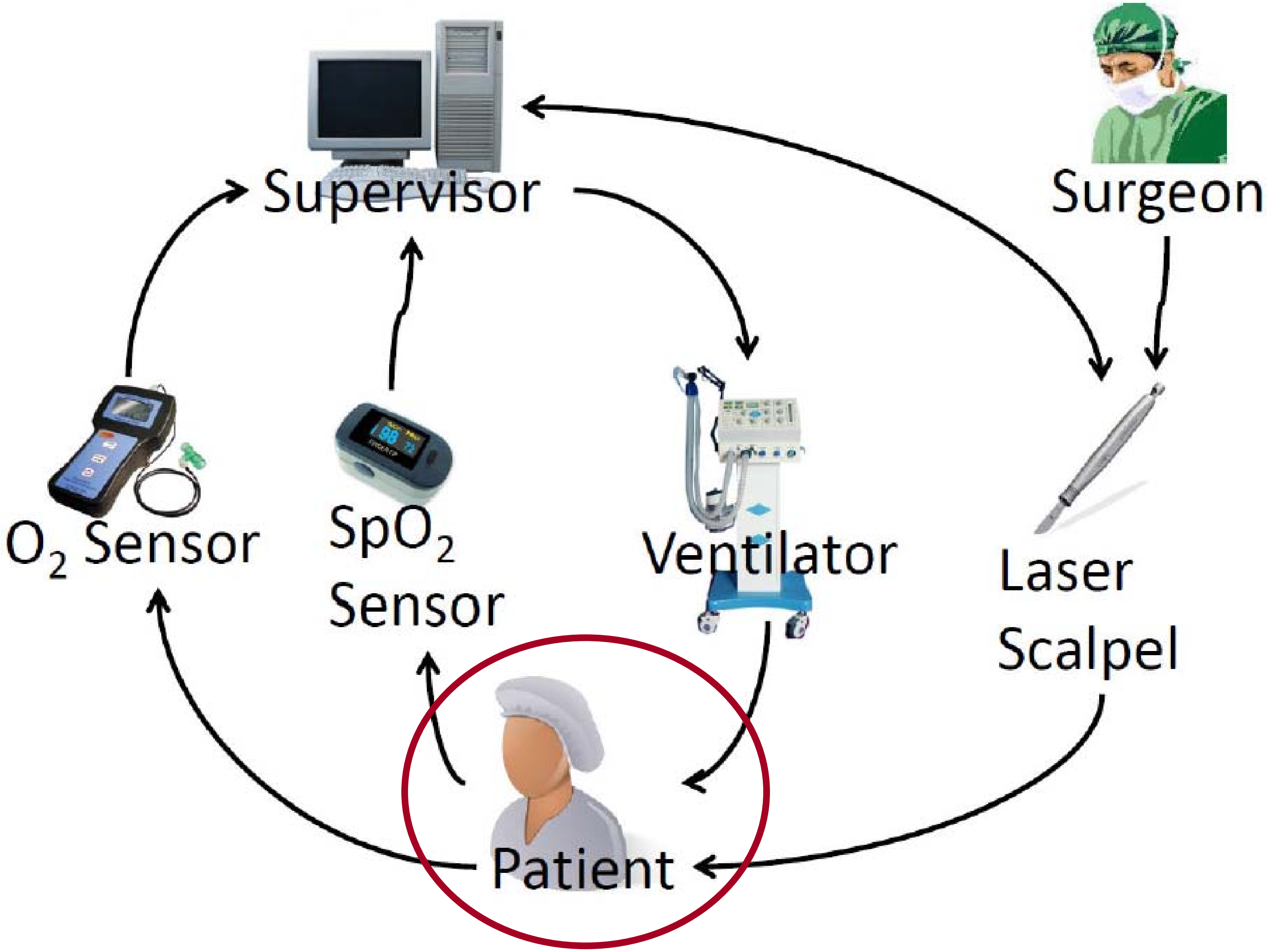
Online → Fixes Many Parameters

Short-Run → Shrink State Space

Let's model the patient again, now online and short-run, with period T.



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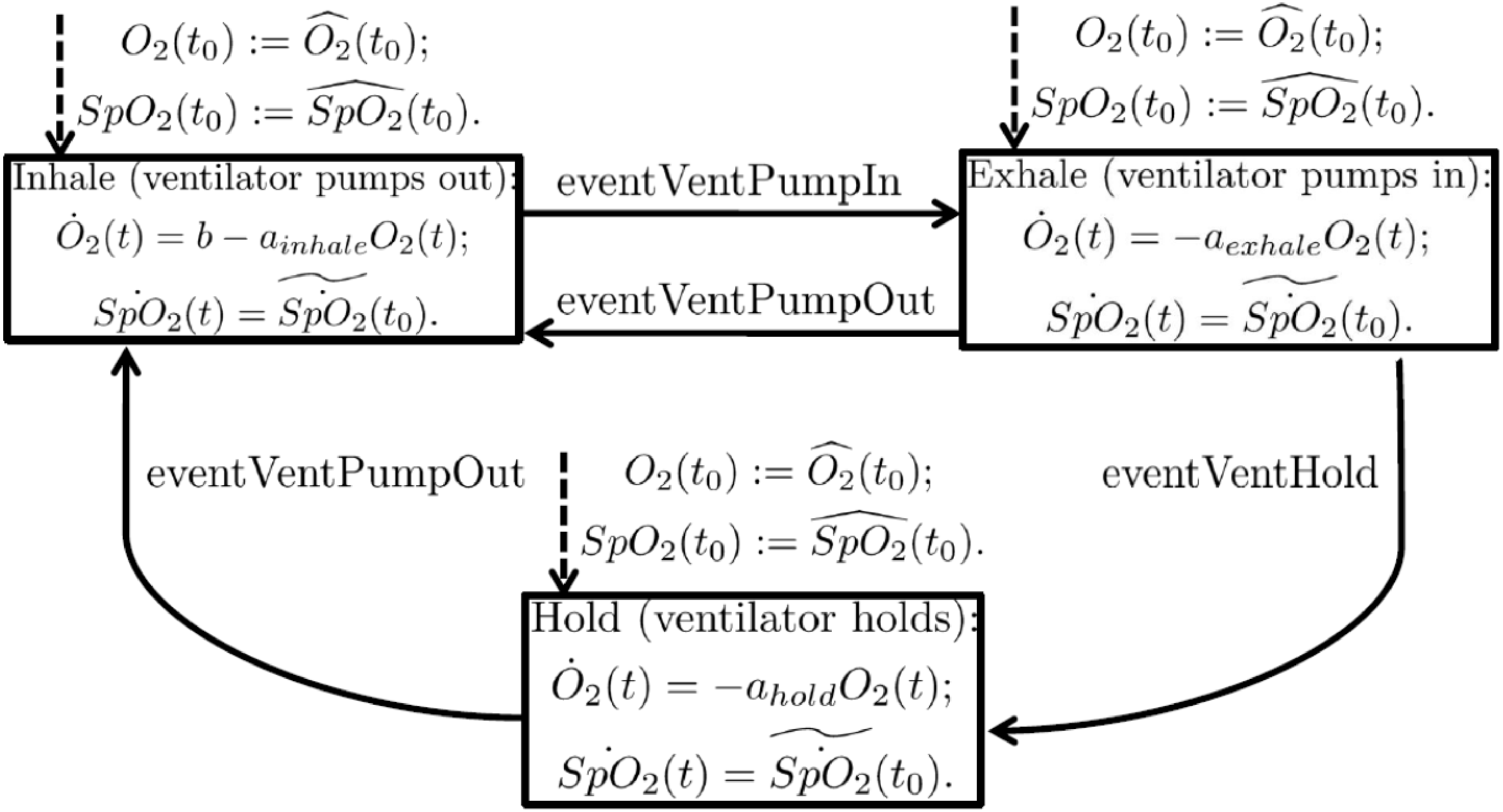

$O_2(t_0) := \widehat{O_2}(t_0);$

$SpO_2(t_0) := \widehat{SpO_2}(t_0).$

Inhale (ventilator pumps out):

$\dot{O}_2(t) = b - a_{inhale}O_2(t);$

$\dot{SpO_2}(t) = \widetilde{\dot{SpO_2}}(t_0).$

eventVentPumpIn

eventVentPumpOut

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eventVentHold

Hold (ventilator holds):

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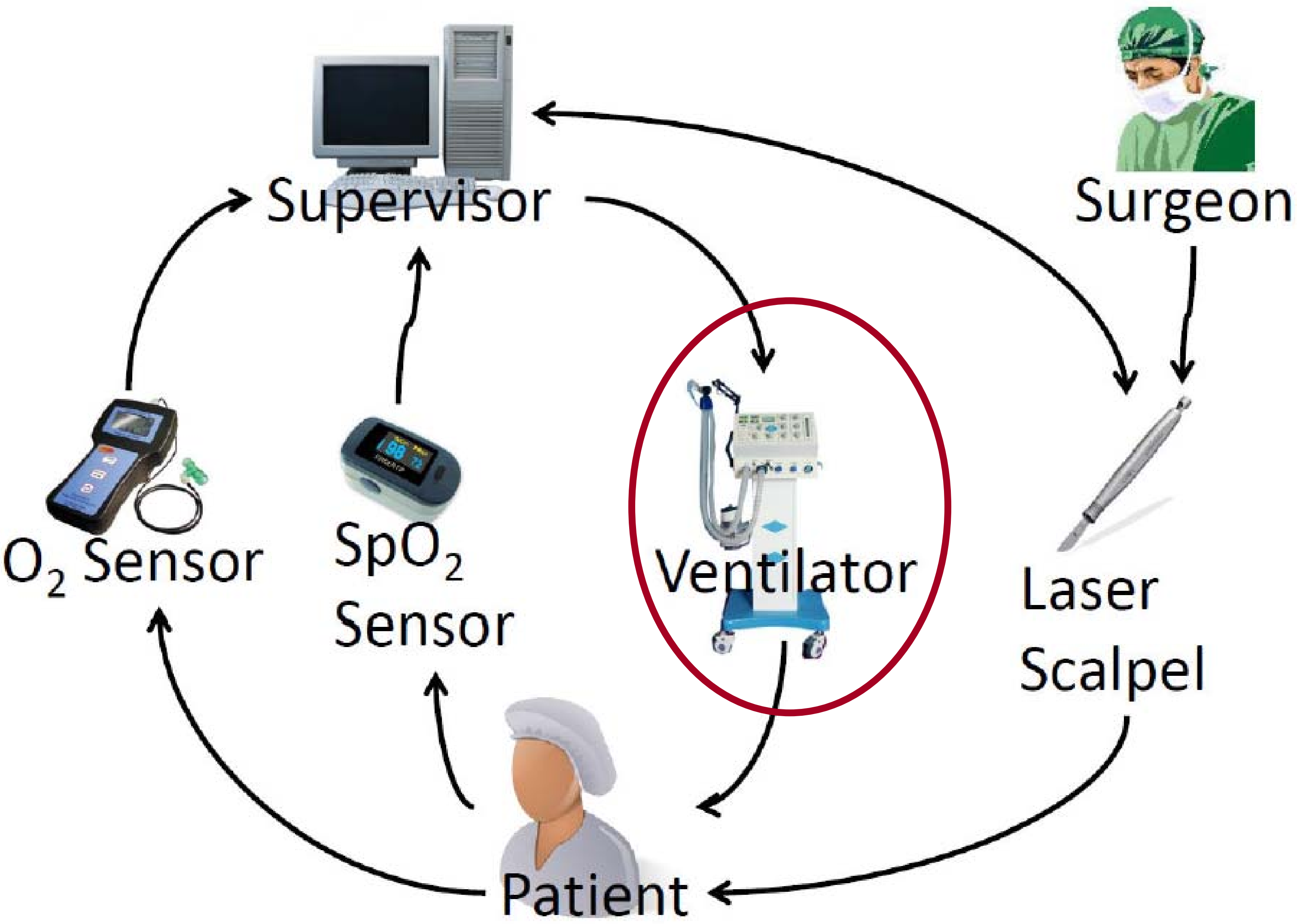
The online short-run model for ventilator.



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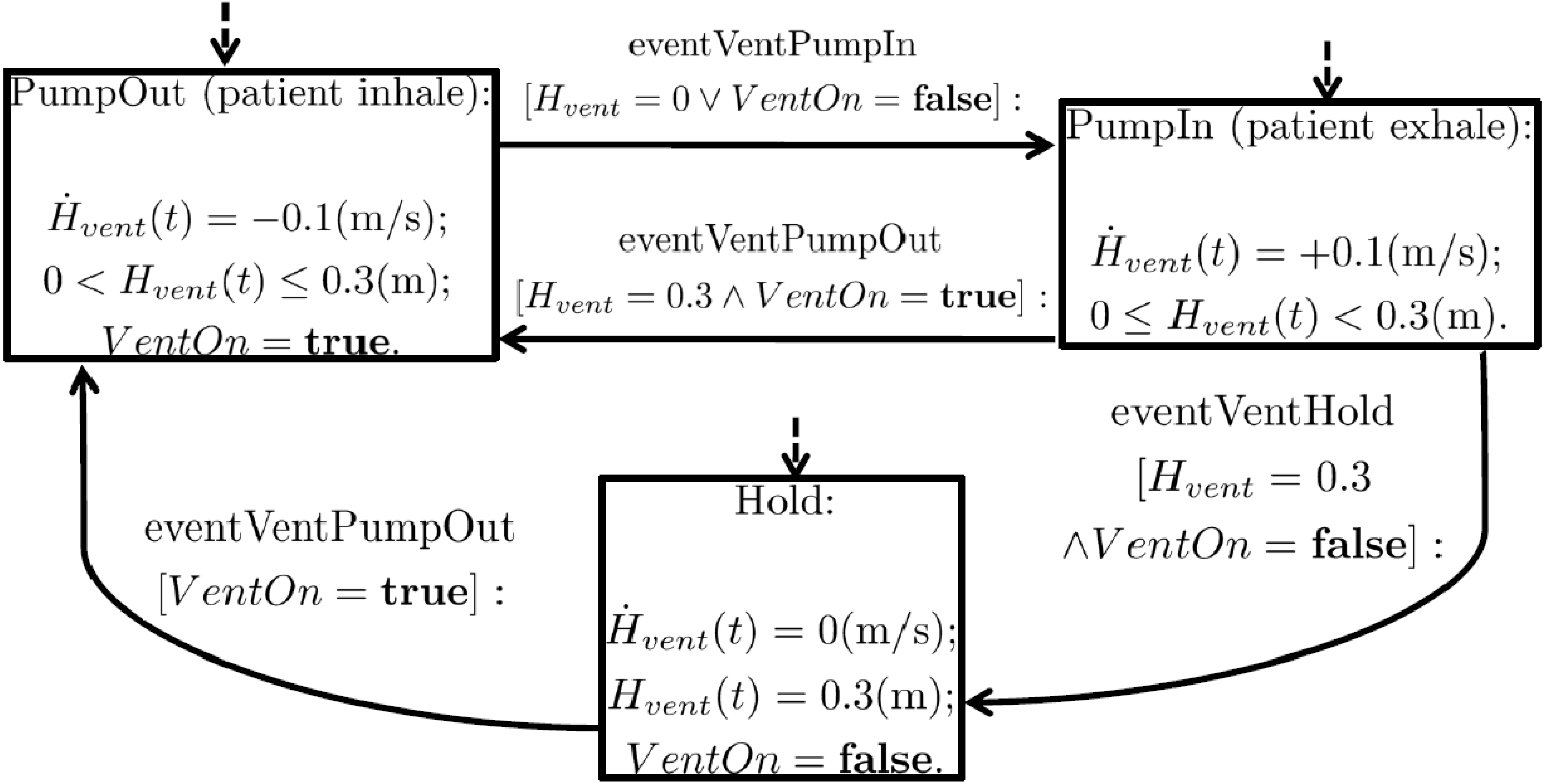

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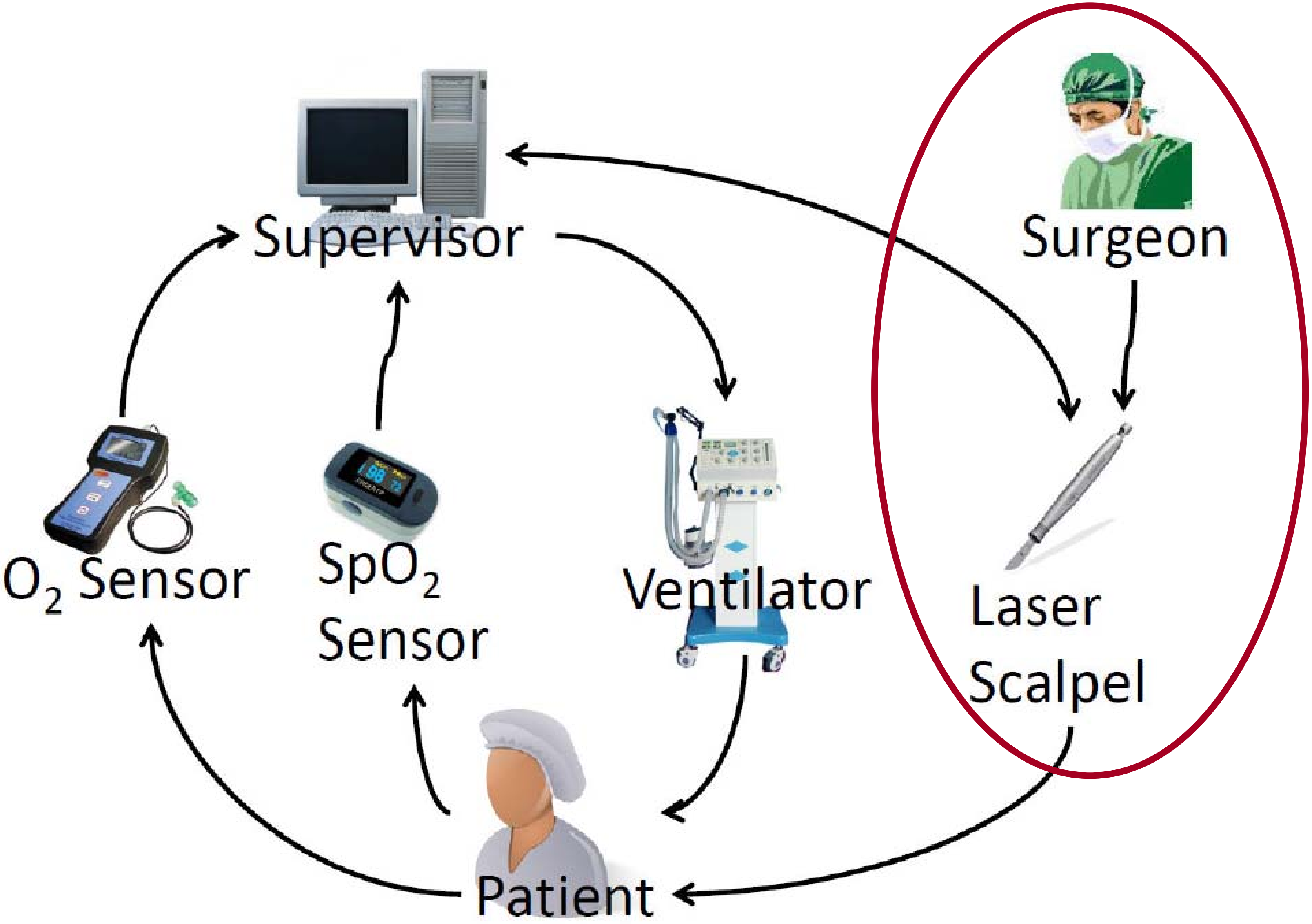
eventVentPumpOut

$[VentOn = \textbf{true}]:$

The online short-run model for laser-scalpel.



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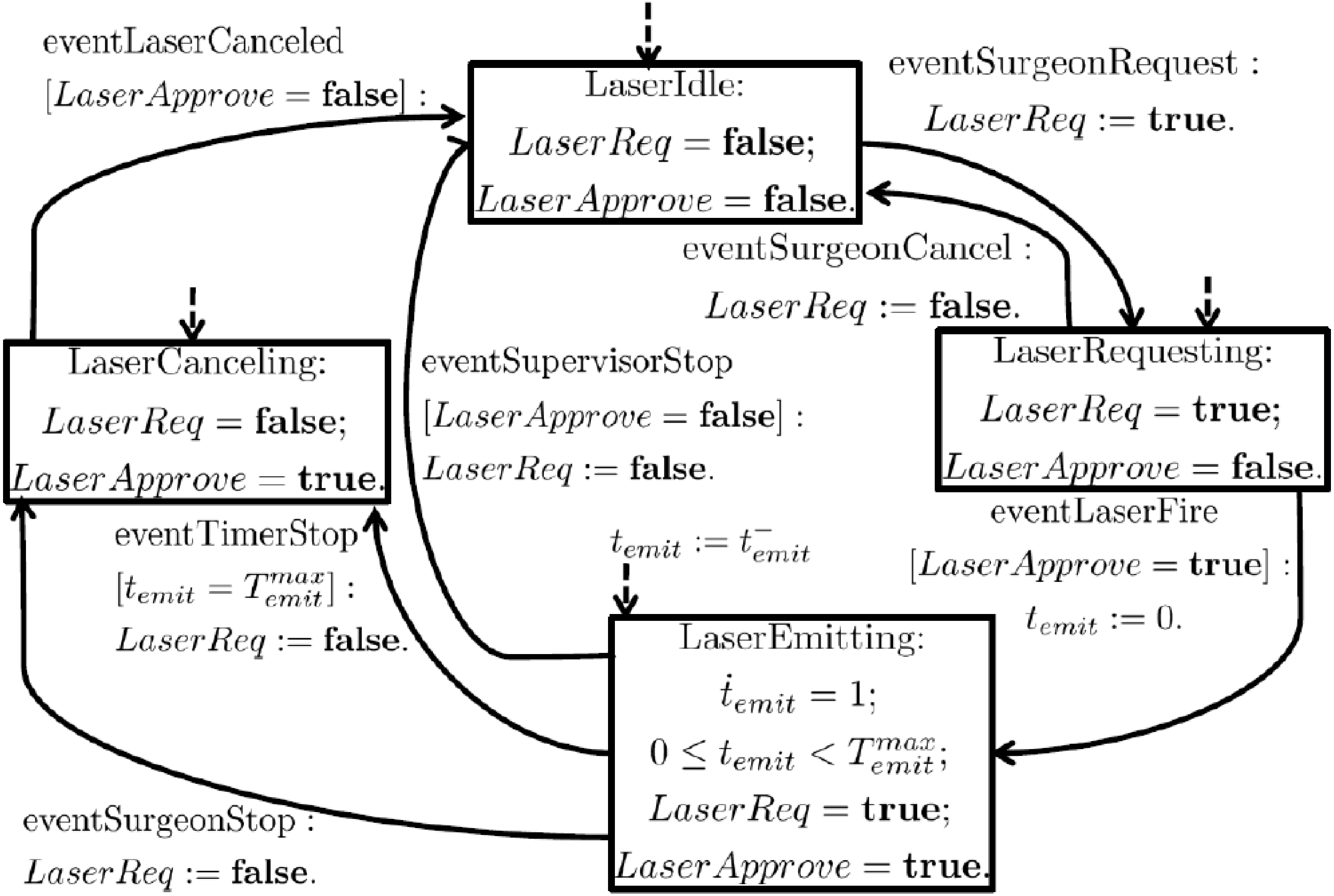


eventLaserCanceled

$[LaserApprove = \textbf{false}]$:

LaserIdle:

$LaserReq = \textbf{false};$

$LaserApprove = \textbf{false}.$

eventSurgeonRequest :

$LaserReq := \textbf{true}.$

eventSurgeonCancel :

$LaserReq := \textbf{false}.$

LaserCanceling:

$LaserReq = \textbf{false};$

$LaserApprove = \textbf{true}.$

eventSupervisorStop

$[LaserApprove = \textbf{false}]$:

$LaserReq := \textbf{false}.$

LaserRequesting:

$LaserReq = \textbf{true};$

$LaserApprove = \textbf{false}.$

eventLaserFire

$[LaserApprove = \textbf{true}]$:

$t_{emit} := 0.$

eventTimerStop

$[t_{emit} = T_{emit}^{max}]$:

$LaserReq := \textbf{false}.$

$t_{emit} := t_{emit}^{-}$

LaserEmitting:

$\dot{t}_{emit} = 1;$

$0 \leq t_{emit} < T_{emit}^{max};$

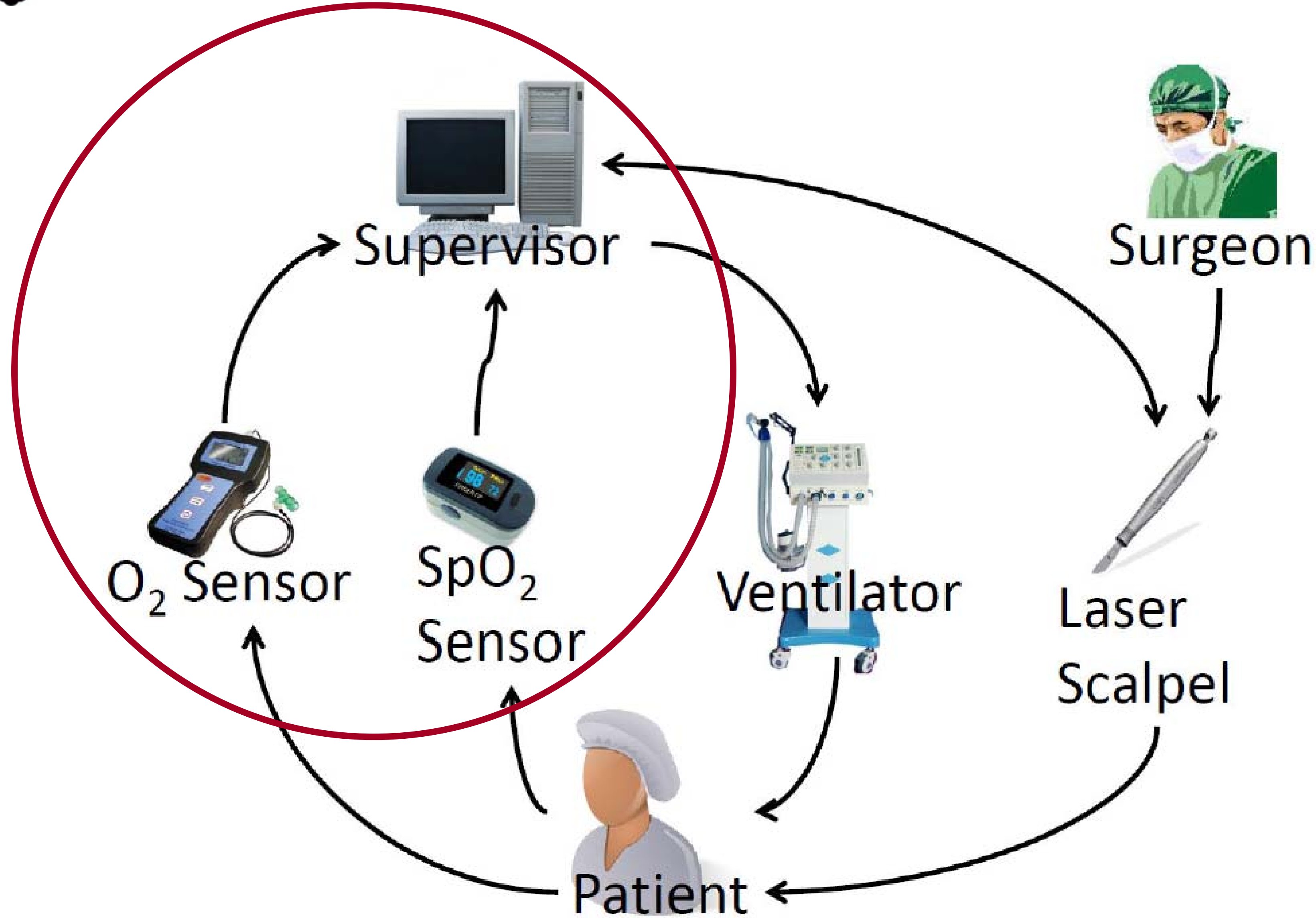
$LaserReq = \textbf{true};$

$LaserApprove = \textbf{true}.$

eventSurgeonStop :

$LaserReq := \textbf{false}.$

The online short-run model for supervisor.



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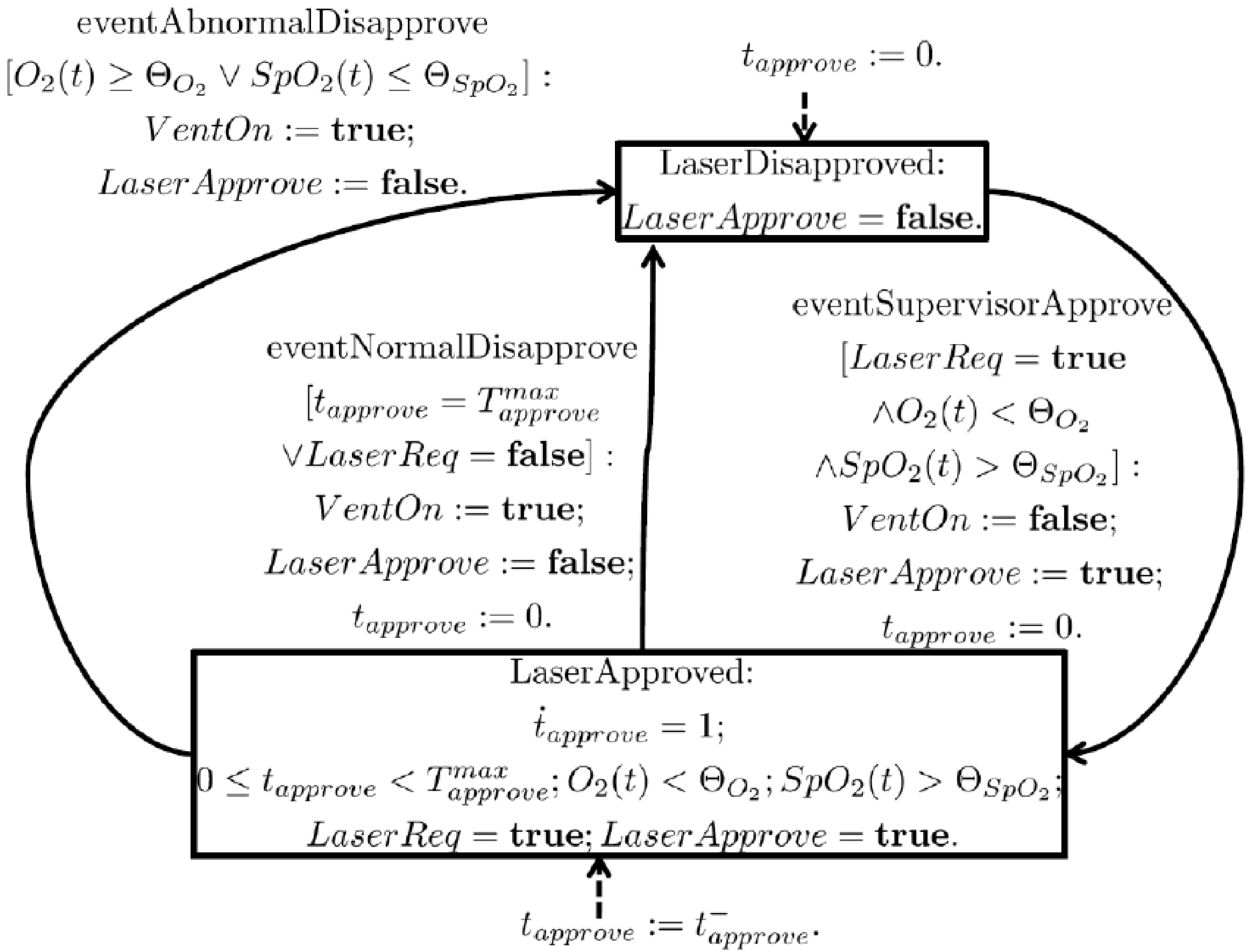

eventAbnormalDisapprove

$[O_2(t) \geq \Theta_{O_2} \vee SpO_2(t) \leq \Theta_{SpO_2}]$:

$VentOn :=$ **true**;

$LaserApprove :=$ **false**.

$t_{approve} := 0.$

LaserDisapproved:

$LaserApprove =$ **false**.

eventNormalDisapprove

$[t_{approve} = T^{max}_{approve}$

$\vee LaserReq =$ **false**$]$:

$VentOn :=$ **true**;

$LaserApprove :=$ **false**;

$t_{approve} := 0.$

eventSupervisorApprove

$[LaserReq =$ **true**

$\wedge O_2(t) < \Theta_{O_2}$

$\wedge SpO_2(t) > \Theta_{SpO_2}]$:

$VentOn :=$ **false**;

$LaserApprove :=$ **true**;

$t_{approve} := 0.$

LaserApproved:

$\dot{t}_{approve} = 1;$

$0 \leq t_{approve} < T^{max}_{approve}; O_2(t) < \Theta_{O_2}; SpO_2(t) > \Theta_{SpO_2};$

$LaserReq =$ **true**; $LaserApprove =$ **true**.

$t_{approve} := t^{-}_{approve}.$

Question: Can the hybrid systems model checking finish (terminate) within period T?

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Hybrid Systems Model Checking → undecidable

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We proved a well-known reachability calculation procedure terminates within polynomial time.

Question: Can the hybrid systems model checking finish (terminate) within period T ?

Hybrid Systems Model Checking → undecidable

Linear Hybrid Automaton (LHA) model checking → undecidable

Simple Time-Bounded (STB) LHA model checking →

We proved a well-known reachability calculation procedure terminates within polynomial time.

STB LHA is powerful enough to describe laser tracheotomy scenario, a representative MDPnP application.

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Emulated Oxymeter and O2 sensor using NIH PhysioNet real-world patient vital sign traces.

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Sampling/Model-Checking Period: $T = 3$ second.

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Hand written online model generator + PHAVer hybrid systems model checker

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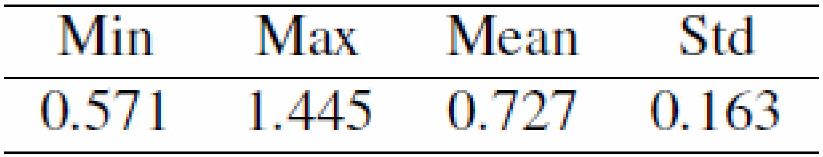
Sampling/Model-Checking Period: $T = 3$ second.

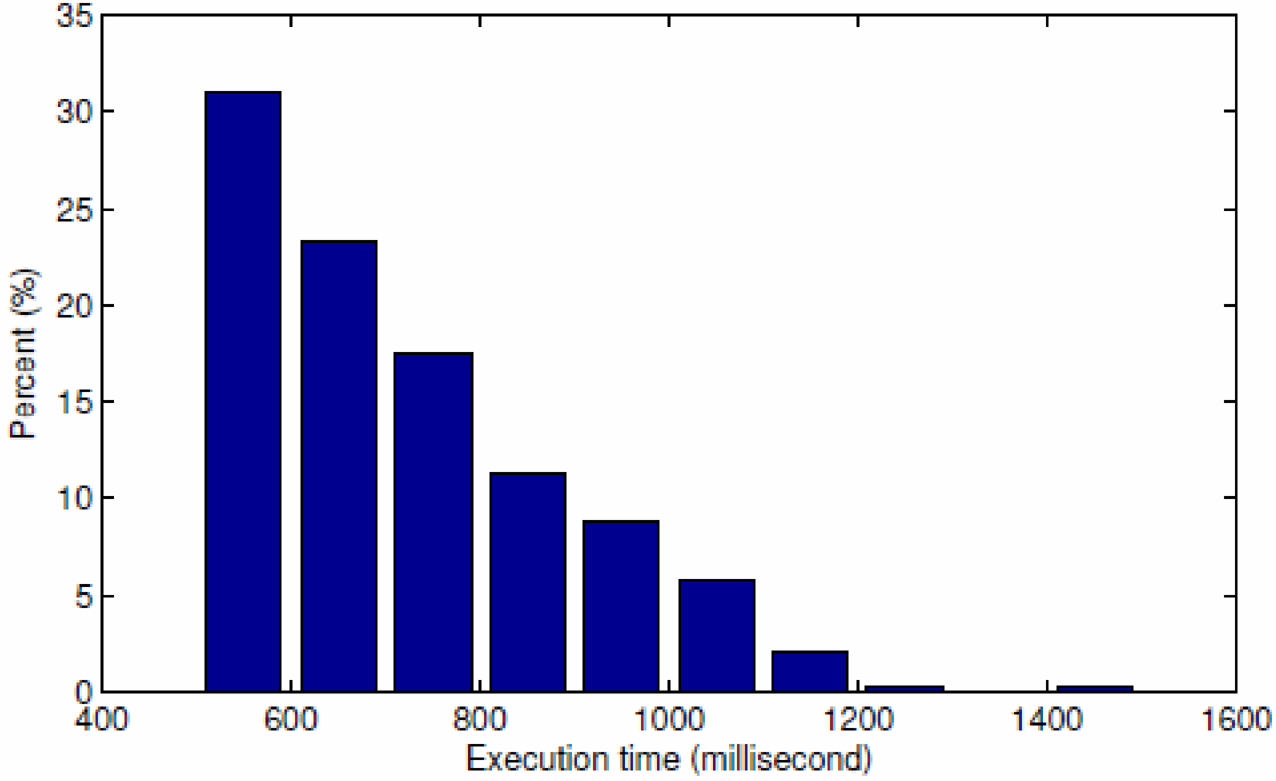
Hand written online model generator + PHAVer hybrid systems model checker

Lenovo Thinkpad X201 + Intel Core i5
+ 2.9G Mem + 32-bit Ubuntu 10.10

Statistics of execution (modeling + checking) time cost: real-time feasible (with pipelining).

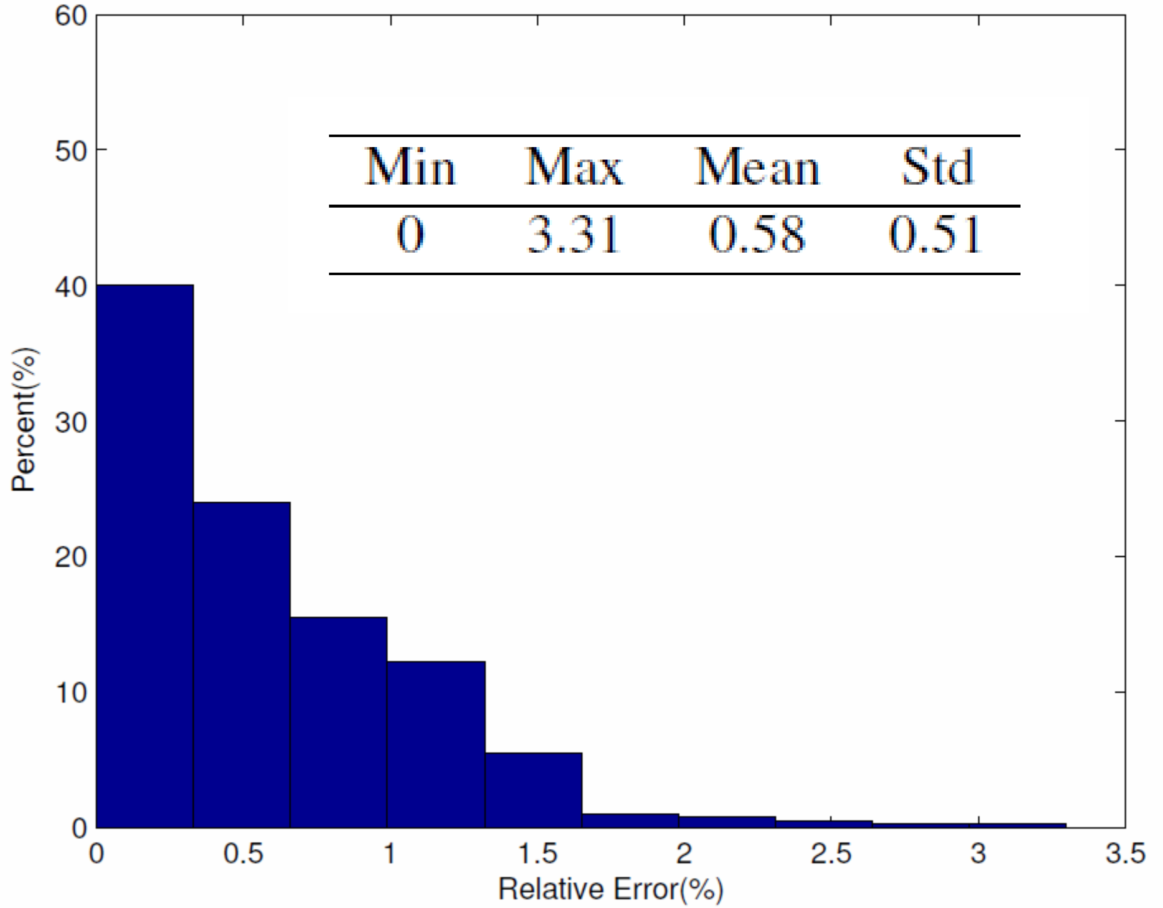


Min	Max	Mean	Std
0.571	1.445	0.727	0.163



Statistics of online SpO_2 prediction accuracy

$$ERR_{SpO_2}(t_0+T) = \frac{|\widehat{SpO}_2(t_0+T) - \widetilde{SpO}_2(t_0+T)|}{\widehat{SpO}_2(t_0+T)}$$



Min	Max	Mean	Std
0	3.31	0.58	0.51

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Runtime Verification [finkbeiner02]

Online discrete systems model checking [qi09][easwaran06]

Other hybrid systems model checkers [robby03][bartocci08]

Thank You!

References

[bartocci08] E. Bartocci, F. Corradini, E. Entcheva, R. Grosu, and S. A. Smolka, Cellexcite: An efficient simulation environment for excitable cells. BMC Bioinformatics, 9(2):1-13, Mar. 2008.

[easwaran06] Arvind Easwaran, Sampath Kannan, Oleg Sokolsky: Steering of Discrete Event Systems: Control Theory Approach. Workshop on Runtime Verification 2006.

[finkbeiner02] B. Finkbeiner, S. Sankaranarayanan, and H. Sipma, Collecting statistics over runtime executions. ENTCS, 70:4, 2002

[qi09] Z. Qi, A. Liang, H. Guan, M. Wu, and Z. Zhang, A hybrid model checking and runtime monitoring method for c++ web services. Proc. of the Fifth International Joint Conference on INC, IMS and IDC, 2009.

[robby03] Robby, M. B. Dwyer, and J. Hatcliff. Bogor: An extensible and highly-modular software model checking framework. Proc. of the 9th European Software Engineering Conference (ESEC/FSE-11), 2003.

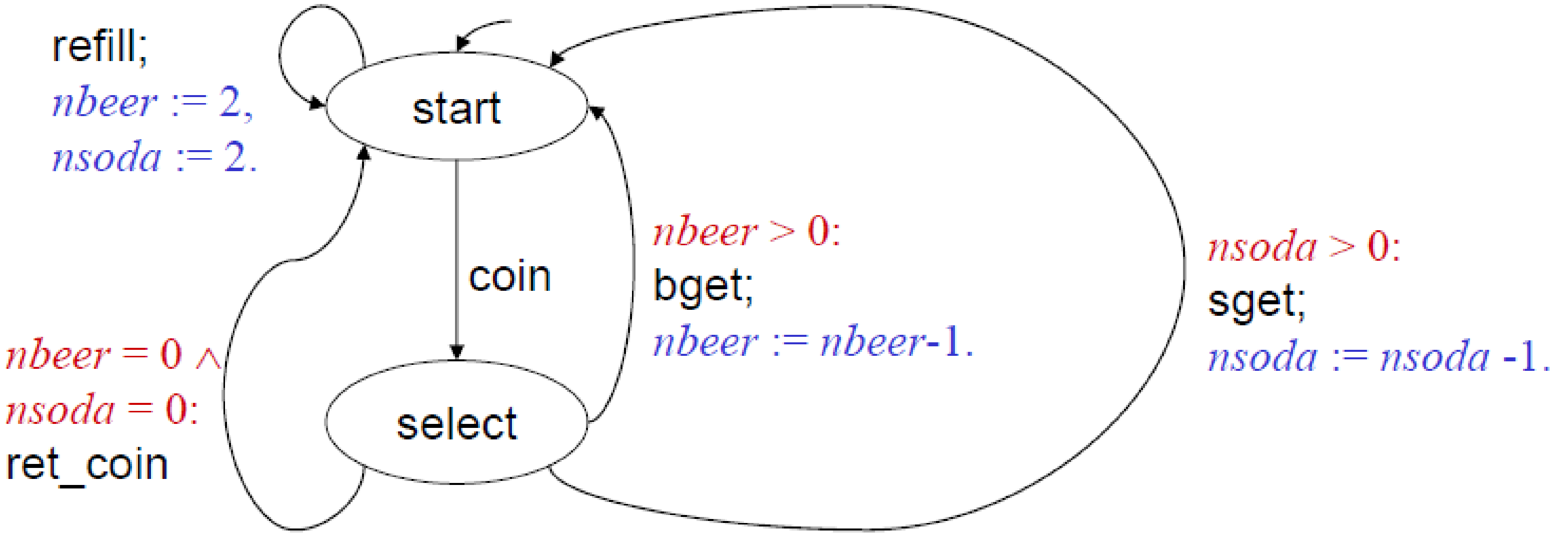
Backup

A key tool for traditional (computer systems) verification is model checking.

$$PG = (Loc, Act, Effect, :\rightarrow, Loc_0, g_0)$$

Set of Locations, e.g., {start, select}

Set of Actions, e.g., {bget, sget, coin, ret_coin, refill}



$$Var = \{nbeer, nsoda\}, \text{domain}(nbeer) = \{0, 1, 2\}, \text{domain}(nsoda) = \{0, 1, 2\}$$

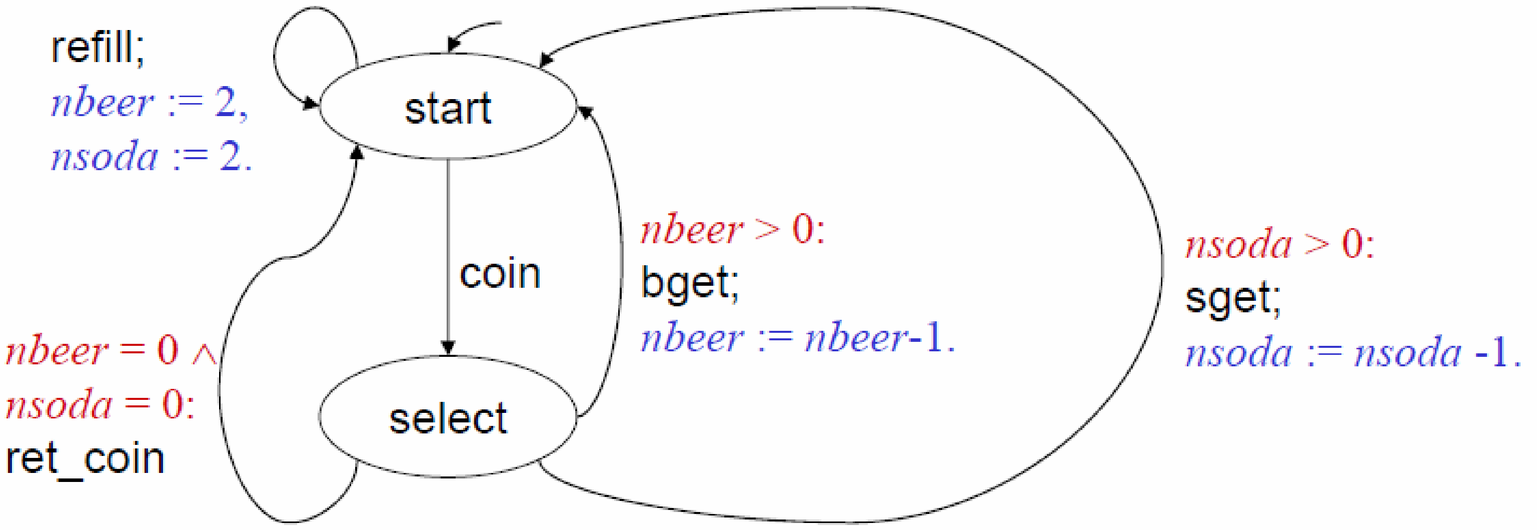
A key tool for traditional (computer systems) verification is model checking.

$$PG = (Loc, Act, Effect, :\rightarrow, Loc_0, g_0)$$

Effect Function : $Act \times Eval(Var) \mapsto Eval(Var)$, e.g.,

$Effect(\text{coin}, \eta) = \eta$, $Effect(\text{ret\_coin}, \eta) = \eta$, $Effect(\text{sget}, \eta) = \eta[nsoda := nsoda - 1]$,

$Effect(\text{bget}, \eta) = \eta[nbeer := nbeer - 1]$, $Effect(\text{refill}, \eta) = [nsoda := 2, nbeer := 2]$.



$Var = \{nbeer, nsoda\}$, domain($nbeer$) = $\{0, 1, 2\}$, domain($nsoda$) = $\{0, 1, 2\}$

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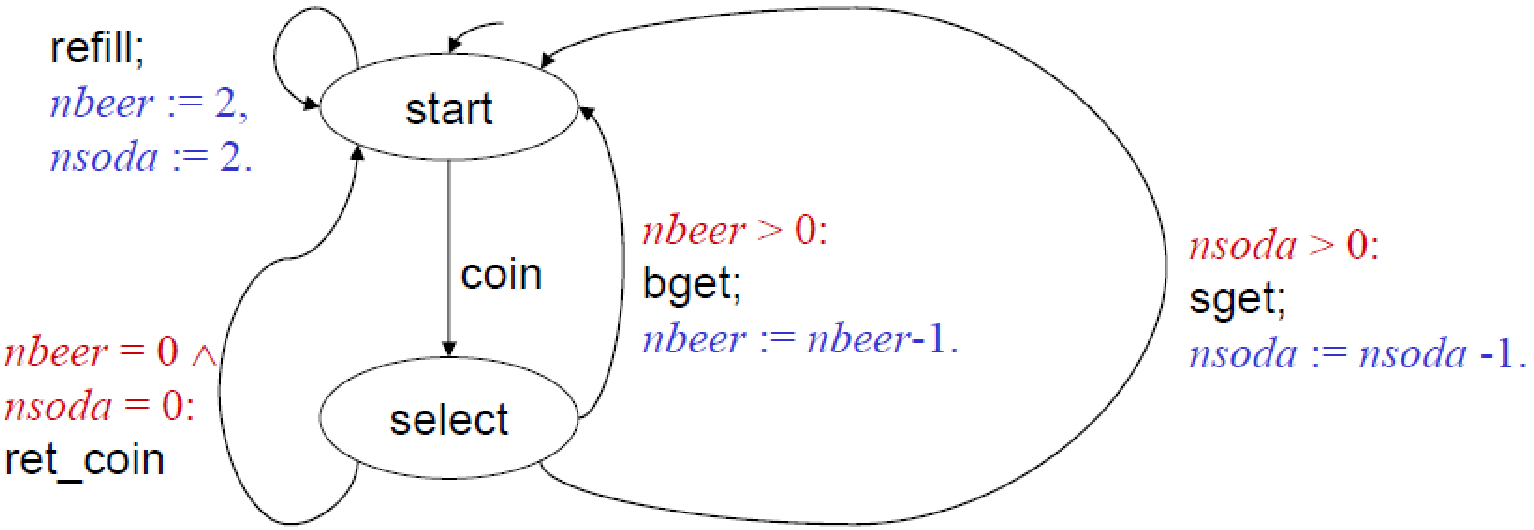
$$PG = (Loc, Act, Effect, :\rightarrow, Loc_0, g_0)$$

Conditional Transition Relation : $\subseteq Loc \times Cond(Var) \times Act \times Loc$.

Often use shortcut $l : \xrightarrow{g:\alpha} l'$ instead of (l, g, α, l');

in cases where $g = true$, use $l : \xrightarrow{\alpha} l'$.



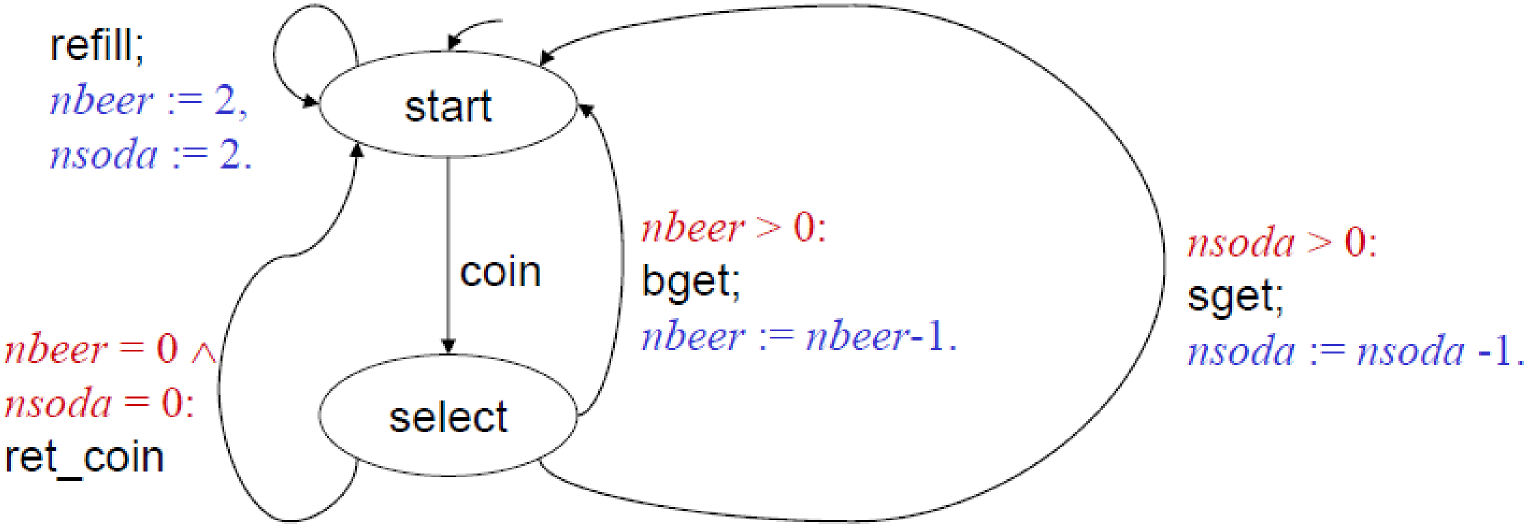
$Var = \{nbeer, nsoda\}$, domain($nbeer$) = {0, 1, 2}, domain($nsoda$) = {0, 1, 2}

A key tool for traditional (computer systems) verification is model checking.

$$PG = (Loc, Act, Effect, :\rightarrow, Loc_0, g_0)$$

$\subseteq Loc$, Set of Initial Locations, e.g., {start}

Initial Condition



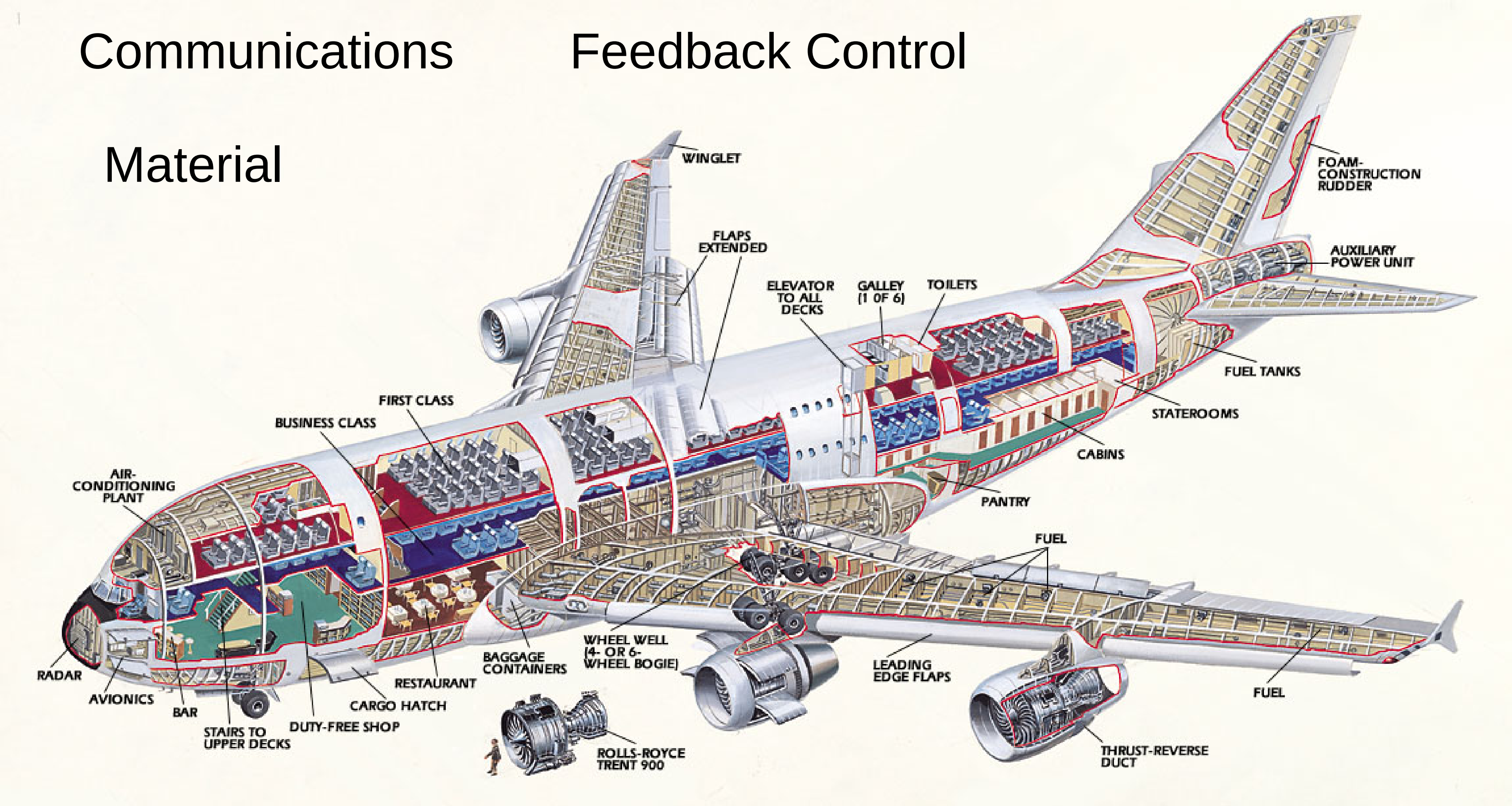
$Var = \{nbeer, nsoda\}$, $\mathrm{domain}(nbeer) = \{0, 1, 2\}$, $\mathrm{domain}(nsoda) = \{0, 1, 2\}$

MDPnP is not just computer systems, it is a hybrid of computer & other systems, i.e., CPS.

Computer Mechanics Aerodynamics

Communications Feedback Control

Material



WINGLET
FOAM-CONSTRUCTION RUDDER
FLAPS EXTENDED
AUXILIARY POWER UNIT
ELEVATOR TO ALL DECKS
GALLEY (1 OF 6)
TOILETS
FUEL TANKS
FIRST CLASS
STATEROOMS
BUSINESS CLASS
CABINS
AIR-CONDITIONING PLANT
PANTRY
FUEL
WHEEL WELL (4- OR 6-WHEEL BOGIE)
BAGGAGE CONTAINERS
LEADING EDGE FLAPS
RADAR
RESTAURANT
FUEL
AVIONICS
CARGO HATCH
BAR
DUTY-FREE SHOP
STAIRS TO UPPER DECKS
ROLLS-ROYCE TRENT 900
THRUST-REVERSE DUCT