A Causal Agent Quantum Ontology

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Overview

- Need for foundational scientific theory with explicit place for *agency*
- Mathematical models of causal agents in artificial intelligence, engineering and social sciences
- Von Neumann quantum theory as causal agent theory

Agency

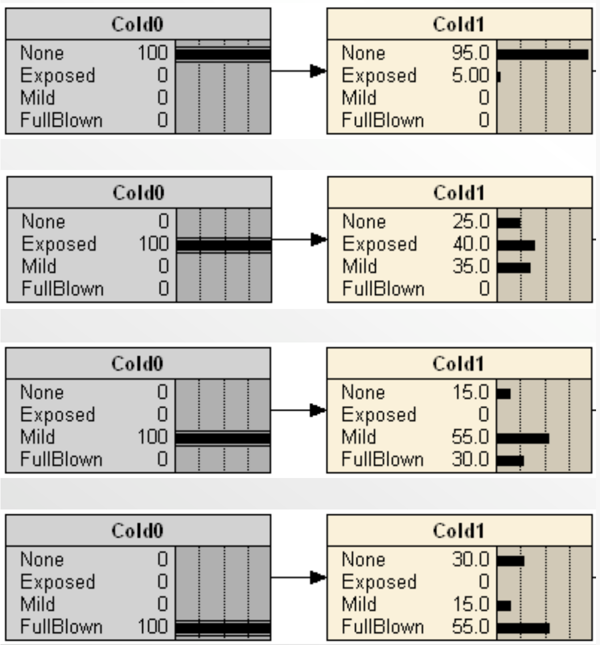
- Humans experience ourselves as *agents*
  - We *choose* from among physically allowable options
  - Options are *constrained* by laws of physics
  - Choice is *not determined* by laws of physics
  - Our choices are *efficacious* in the physical world
- Our experience of agency is a datum in need of explanation
  - Epiphenomenon?
  - Illusion?
  - Feature of natural world?
- Choice of explanation has consequences

Markov Process

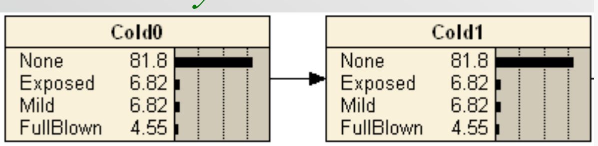
- Time-indexed sequence of states
- Evolves stochastically
- "Memoryless" property:
  - Probability distribution for future states is conditionally independent of past given current state
  - $\Pr(s_1, \ldots, s_n \mid s_0) = \prod_{k=1}^{n} \pi(s_k \mid s_{k-1})$

(*We limit discussion to discrete-event discrete-outcome processes*)

Example: Getting a Cold



Stationary distribution:



- Possible states:
  - None
  - Exposed
  - Mild
  - FullBlown

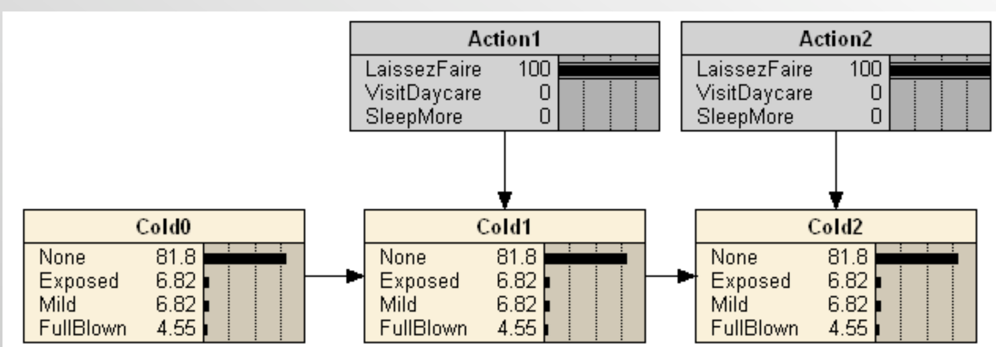
- Probability of current state depends on previous state
- Memoryless

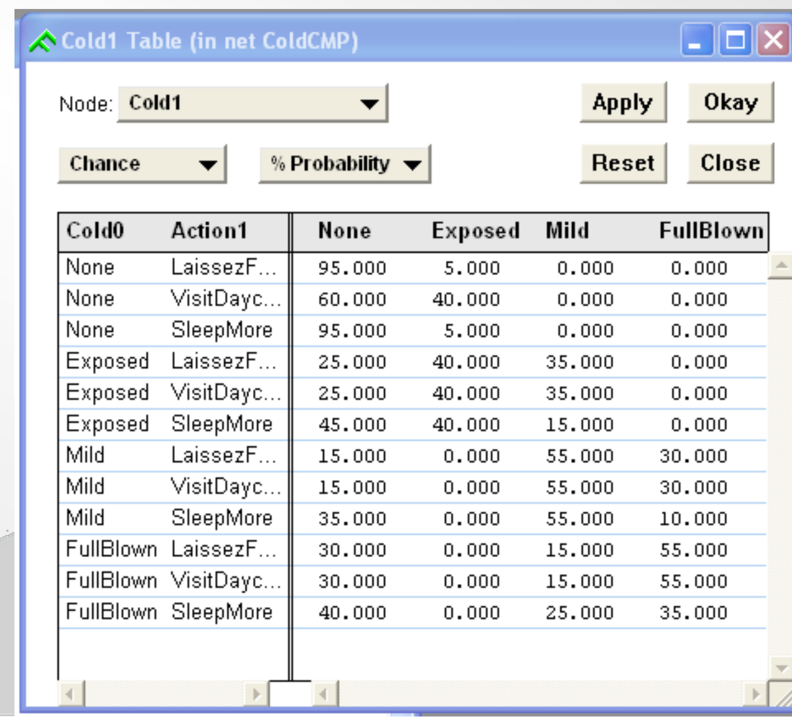
Causal Markov Process

- Mathematical model for effects of interventions
- Family of Markov processes
  - Set of *actions*
  - Actions represent possible interventions into evolution of system
  - Distribution of state depends on past state and past action
  - Actions may depend on history of prior actions and states
  - $\Pr(s_1,\ldots,s_n \mid a_1,\ldots,a_n,s_0) = \prod_{k=1}^{n} \theta(a_k \mid h_k)\pi(s_k \mid s_{k-1},a_k)$
- Distribution for actions is called a *policy*
- There is a Markov process for each policy
  - Transition probabilities *depend on policy*

Example: Influencing a Cold

- No-intervention process is same as original process
- There are actions that affect chance of getting or recovering from cold
  - Visiting daycare center increases chance that well person will be exposed
  - Sleeping more decreases chance of progression and increases chance of recovery if exposed or sick





Cold0	Action1	None	Exposed	Mild	FullBlown
None	LaissezF...	95.000	5.000	0.000	0.000
None	VisitDayc...	60.000	40.000	0.000	0.000
None	SleepMore	95.000	5.000	0.000	0.000
Exposed	LaissezF...	25.000	40.000	35.000	0.000
Exposed	VisitDayc...	25.000	40.000	35.000	0.000
Exposed	SleepMore	45.000	40.000	15.000	0.000
Mild	LaissezF...	15.000	0.000	55.000	30.000
Mild	VisitDayc...	15.000	0.000	55.000	30.000
Mild	SleepMore	35.000	0.000	55.000	10.000
FullBlown	LaissezF...	30.000	0.000	15.000	55.000
FullBlown	VisitDayc...	30.000	0.000	15.000	55.000
FullBlown	SleepMore	40.000	0.000	25.000	35.000

Markov Decision Process

- Causal Markov process with reward
- Each policy defines a Markov process on states and rewards
- Mathematical model for value-driven sequential decisions
  - Action is *chosen by agent*
- Partially observable Markov decision process (POMDP)
  - Full state may not be observable
  - Policy and reward depend only on observables
  - Widely applied in engineering and artificial intelligence
  - Aim is to find optimal or near-optimal policies that are tractable to compute and feasible to implement

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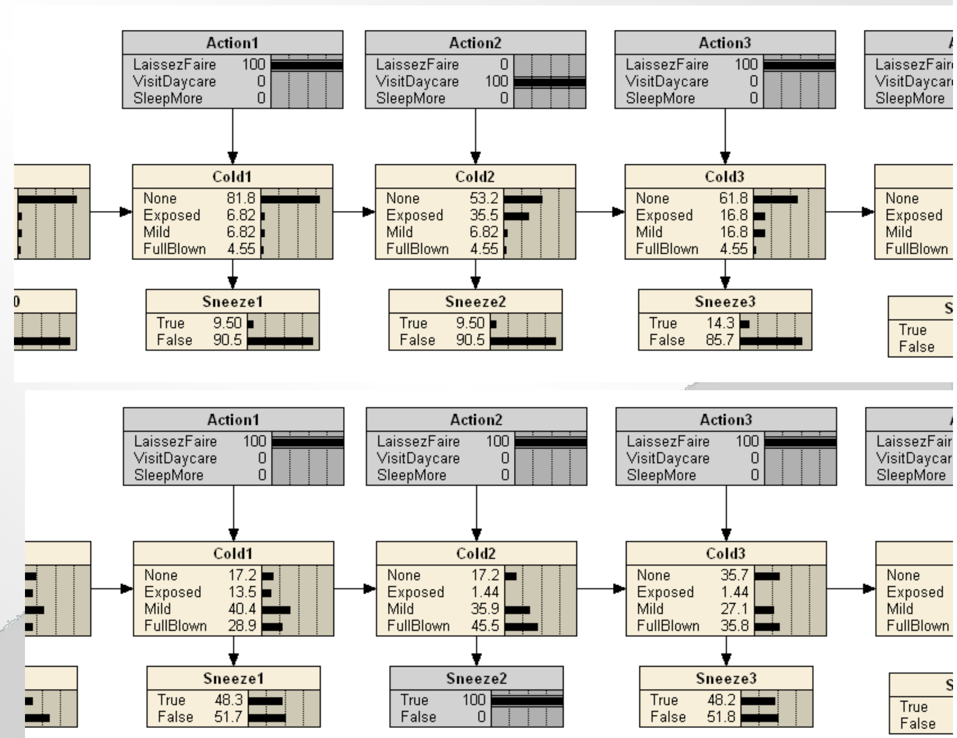
That Darned Cold Again!

- State is unobservable
- Observable symptom: sneezing
  - 2% chance if none or exposed
  - 50% chance if mild
  - 95% chance if full-blown
- Rewards:
  - Sneezing is very bad (reward -8)
  - Visiting daycare is good (reward 1)
  - Too much sleep is bad (reward -1)
- Require *myopic* policy (depends only on previous observable and action)

Policy	Average Expected Reward	Chance of No Cold
Always LaissezFaire	-0.82	0.82
If Sneeze then VisitDaycare else LaissezFaire	-0.72	0.82
If Sneeze then SleepMore else LaissezFaire	-0.83	0.80
Always SleepMore	-1.3	0.96

Correlation and Causality

- Causal claims are bolder than statements about correlation
  - In addition to summarizing observed relationships among variables, a causal model predicts relationships that continue to hold when cause is manipulated
- Causal relationships are inherently asymmetric
  - *Intervention* changes future predictions but does not change inferences about the past
  - *Information* changes both future predictions and inferences about the past
- Causal knowledge is fundamental to our ability to process information



Quantum State

- Represented by density operator
  - Square complex-valued matrix with non-negative eigenvalues that sum to 1
  - Tensor product space represents composite system
  - State is pure if it has one non-zero eigenvalue and mixed otherwise
- n-dimensional density operator is quantum generalization of classical random variable with n possible outcomes
  - Classical random variable is represented as a diagonal density operator (in basis of classical outcomes)
  - Density operator for quantum system may have non-zero off-diagonal elements
  - Environmental decoherence tends to produce rapid diagonalization in warm, wet bodies of living organisms
  - Decoherence suppresses “weird” effects of quantum superpositions

Evolution of Quantum Systems

- Unitary evolution (von Neumann Process 2)
  - Occurs when closed system evolves passively
  - Reversible transformation
  - Continuous in time
- State reduction (von Neumann Process 1)
  - Occurs when system interacts with environment
  - Irreversible
  - Discontinuous stochastic transition to one of a set of mutually orthogonal subspaces that span the state space
  - Born probability rule yields highly accurate predictions of outcome probabilities

From Two to Four Processes

- Process 0: Pose a question to Nature
  - A set of projection operators is applied at a given time interval after the previous reduction
- Process 1*a*: Form potential answers
  - State changes discontinuously from $\sigma(t\text{-})$ to $\sum_i P_i \sigma(t-) P_i$
- Process 1*b*: Select answer to question
  - State changes discontinuously
  - New state is $\sigma(t+) = P_i\sigma(t\text{-})P_i/\mathrm{Tr}(P_i\sigma(t\text{-})P_i)$ with probability $\mathrm{Tr}(P_i\sigma(t\text{-})P_i)$
- Process 2: Evolve passively between interventions
  - Evolution follows Schrödinger equation for d time units until next intervention
  - Reversible transformation from $\sigma(t+)$ to $U(d)\sigma(t+)U(d)$

Physical Theory of Four Processes

- *Process 0: Pose a question to Nature*
  - *No theory for timing or choice of operator*
  - *Phenomenological experience associates Process 0 with free choices made by scientists*
- Process 1a: Form potential answers
  - Given by quantum theory
- Process 1b: Select answer to question
  - Stochastic choice with probabilities given by quantum theory
- Process 2: Evolve passively between interventions
  - Given by quantum theory

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Quantum Theory as CMP

- States are density operators
- Actions are choices of projection operator and time of application
- Distribution of next state:
  - Independent of past conditional on state at last intervention and intervention applied
  - Probabilities given by Born rule
- Time asymmetry
  - *Interventions affect future but not past*

Quantum Theory as MDP?

- Postulate: Some quantum systems are *agents*
  - Can apply projection operators to degrees of freedom associated with their own bodies
  - Choices are free within not-yet-understood physical constraints
  - Choices affect future evolution of physical world
  - Choices may affect agent's bodily integrity and ability to continue making choices (i.e., survival)
- Darwin: Evolution rewards systems of agents that make choices conducive to survival

Choosing A or B: An Oversimplified Model

- Clear preference for Option A
  - Experience: "I am choosing A"
  - Brain automatically generates ~40 Hz oscillations at sites associated with Option A
- Clear preference for Option B
  - Experience: "I am choosing B"
  - Brain automatically generates ~40 Hz oscillations at sites associated with Option B
- No "automatic winner"
  - Experience: ambivalence until decision
  - Brain automatically generates weakly coupled oscillators with periodic energy transfer between "I am choosing A" and "I am choosing B" until decision is made

(after Stapp, 2007)

Quantum Zeno Effect

- Essentially quantum mechanical phenomenon
- Experimentally confirmed
- How QZE works:

  IF: sequence of similar projection operators is applied in rapid succession

  THEN: System will (with high probability) follow sequence of states corresponding to projection operators
- QZE can be used to direct a system to follow trajectory that differs from automatic evolution
- QZE has been proposed (Stapp, 2007) as a mechanism for efficacious choice

Implementing Choice With QZE

- Choose and implement Option A:
  - Apply projection operator "Am I choosing Option A?"
  - If answer is "yes," then apply rapid sequence of projection operators tracking 40Hz oscillations at sites associated with Option A
  - Otherwise, apply less rapid sequence of projection operators tracking energy transfer between Options A and B
- Result is to select and then "hold in place" pattern of neural correlates for Option A for macroscopic period of time
- This hypothesized mechanism is not destroyed by environmental decoherence

Summary

- Humanity needs a foundational theory of agency
- Quantum theory has an explanatory gap
  - QT explains automatic evolution and response to interventions
  - QT does not explain which interventions occur at what times
- A quantum system with interventions is a causal Markov process
- If we assign interventions to agents, a quantum system is a partially observable Markov decision process
- POMDPs are widely applied as models of agency
- Why not in quantum theory?