Computing and the Environment
Vanderbilt University

Douglas H. Fisher

Planning and Uncertainty

First Order Planning

Representation of operators: A PREcondition list and an EFFects list

pickup(?x): PRE: ONTABLE(?x), CLEAR(?x), HANDEMPTY
EFF: ~ONTABLE(?x), ~CLEAR(?x), ~HANDEMPTY,
HOLDING(?x)

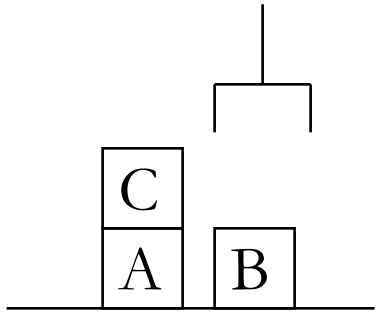
putdown(?x): PRE: HOLDING(?x)
EFF: ~HOLDING(?x),
ONTABLE(?x), CLEAR(?x), HANDEMPTY

stack(?x, ?y): PRE: HOLDING(?x), CLEAR(?y)
EFF: ~HOLDING(?x), ~CLEAR(?y),
HANDEMPTY, ON(?x, ?y), CLEAR(?x)

unstack(?x, ?y): PRE: HANDEMPTY, CLEAR(?x), ON(?x,?y)
EFF: ~HANDEMPTY, ~CLEAR(?x), ~ON(?x,?y),
HOLDING(?x), CLEAR(?y)

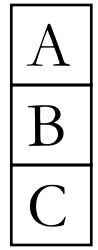
First Order Planning

Tweak : the following slides represent *one* path in a search for a plan



ON(C,A)
ONTAB(A)
ONTAB(B)
CLEAR(B)
CLEAR(C)
HANDEMPTY

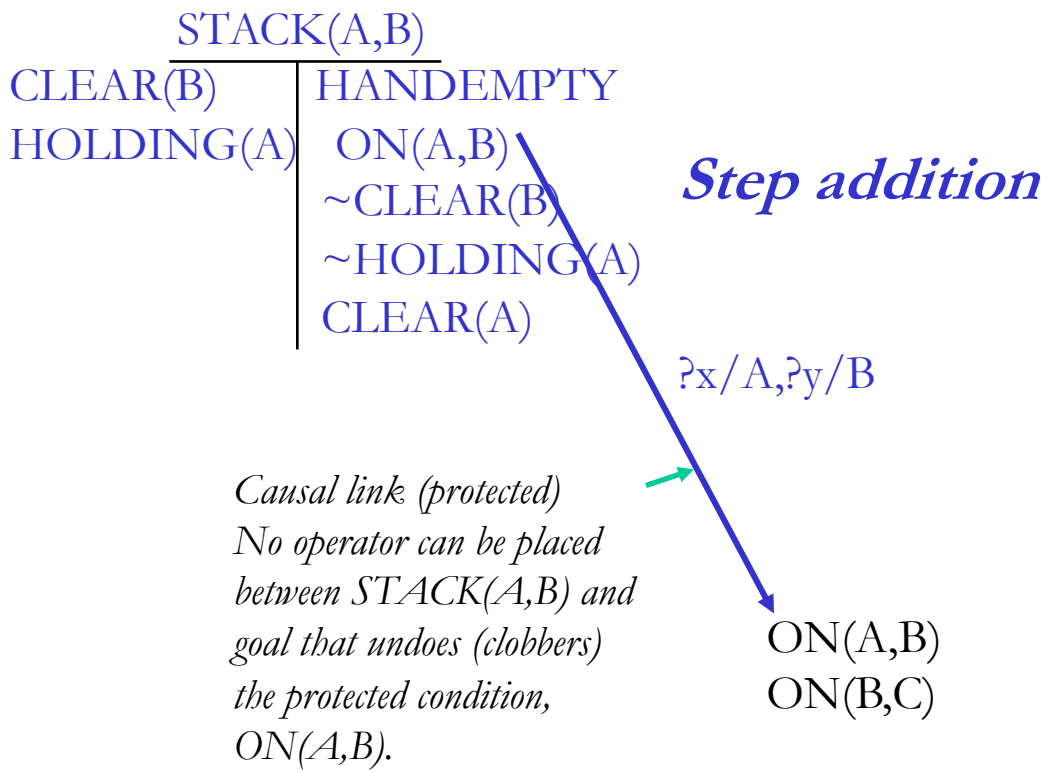
Initial State



ON(A,B)
ON(B,C)

Goal Spec

First Order Planning

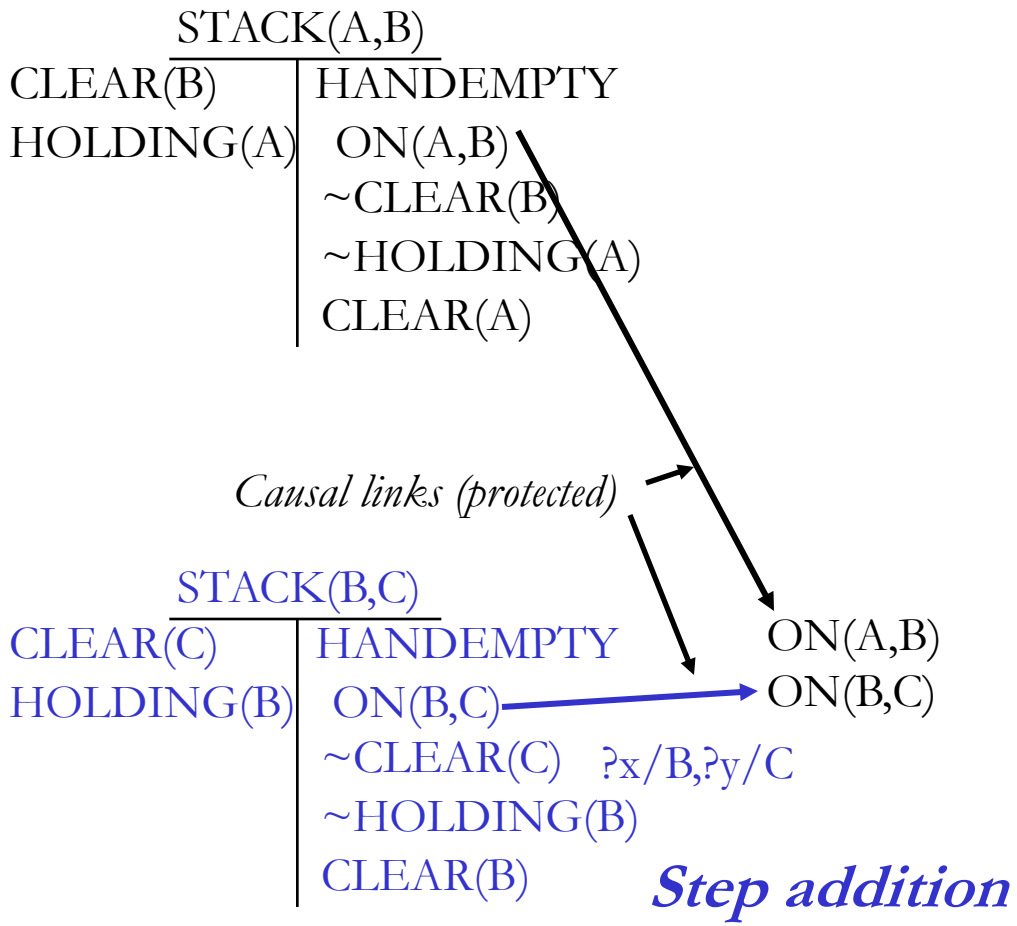


ON(C,A)
ONTAB(A)
ONTAB(B)
CLEAR(B)
CLEAR(C)
HANDEMPTY

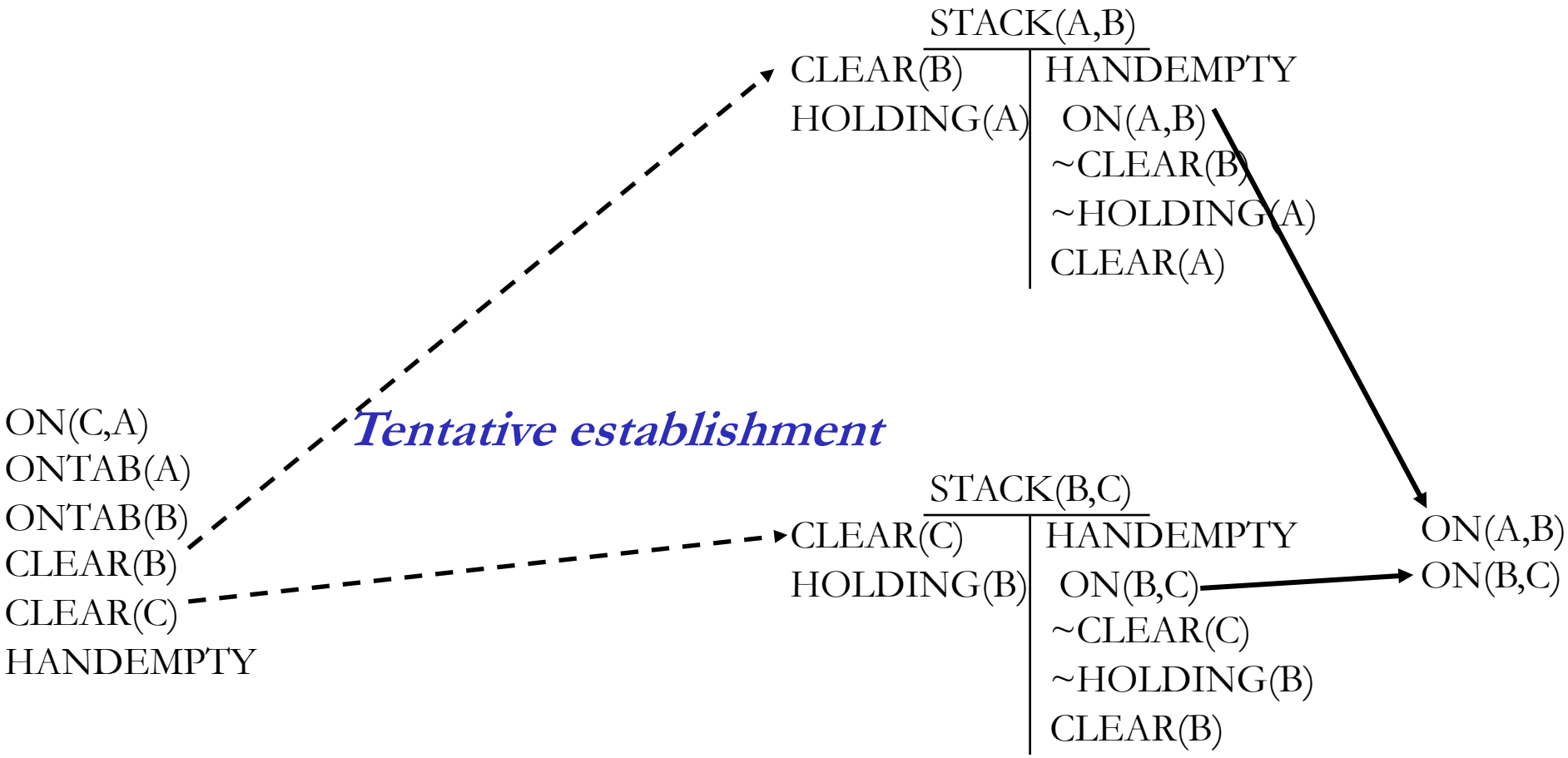
Tweak is described in David Chapman (1987). “Planning for Conjunctive Goals”. Artificial Intelligence, Vol. 32, pp. 333-377 and numerous AI textbooks.

First Order Planning

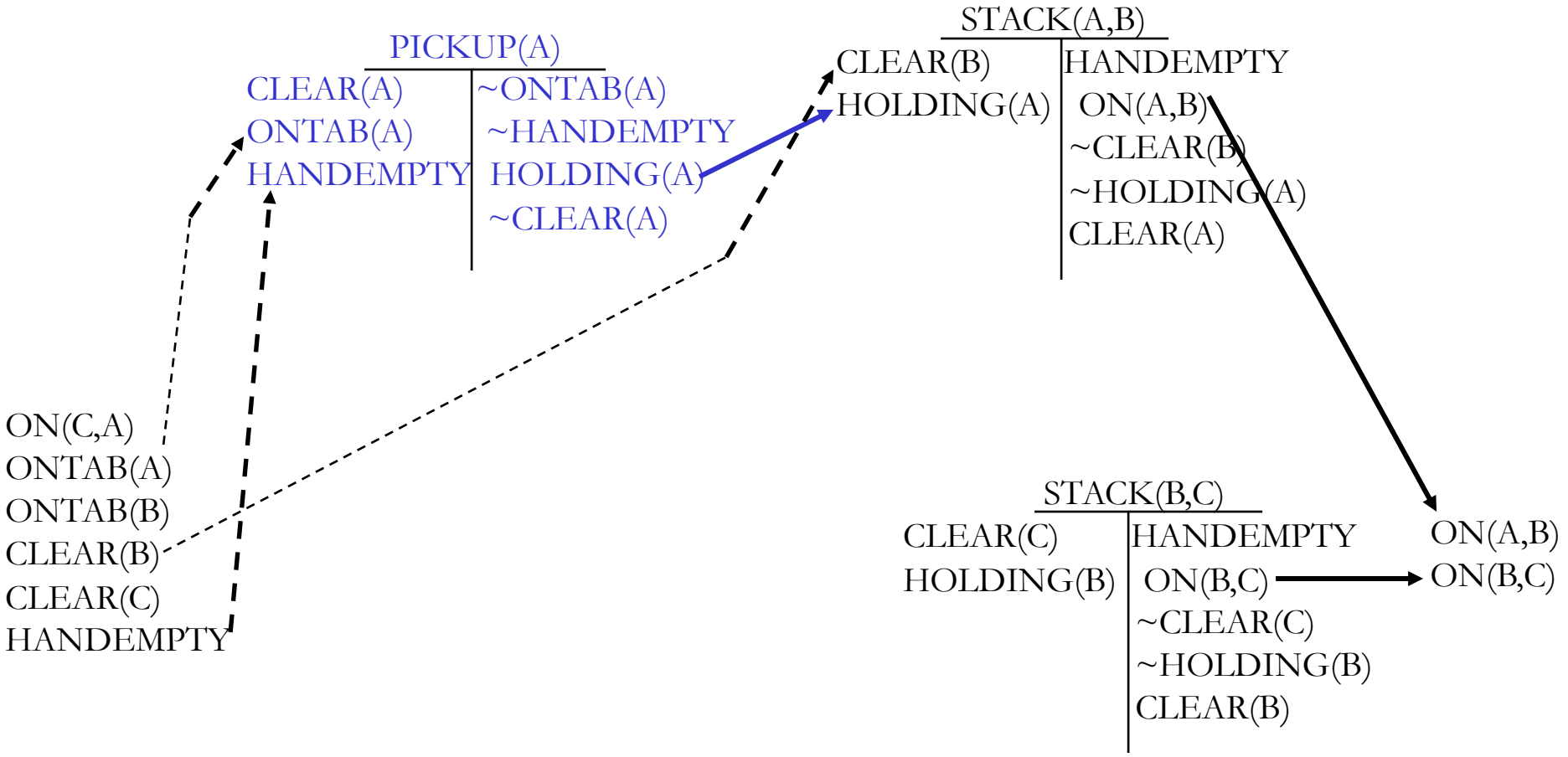
ON(C,A)
ONTAB(A)
ONTAB(B)
CLEAR(B)
CLEAR(C)
HANDEMPTY



First Order Planning

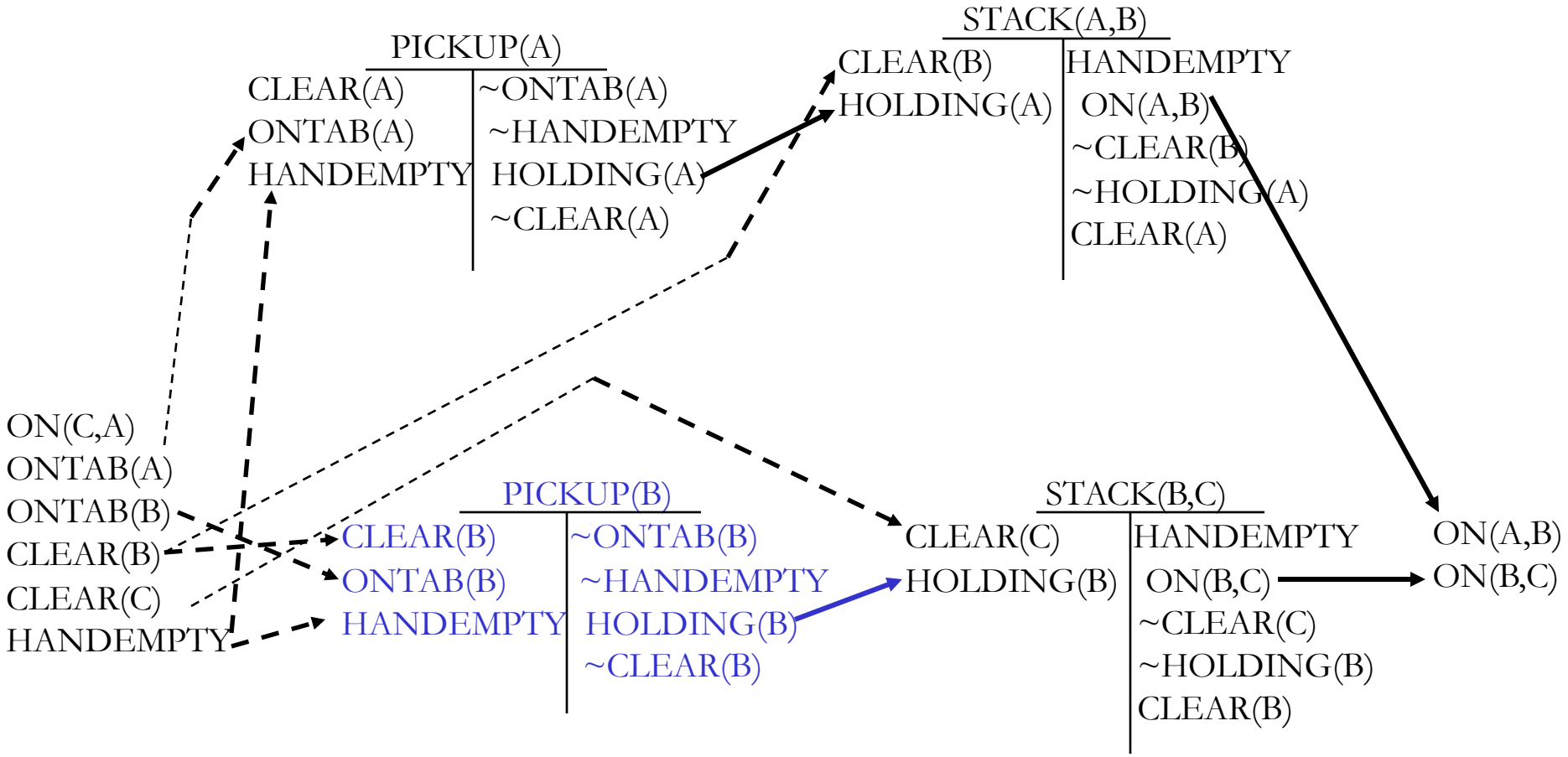


First Order Planning



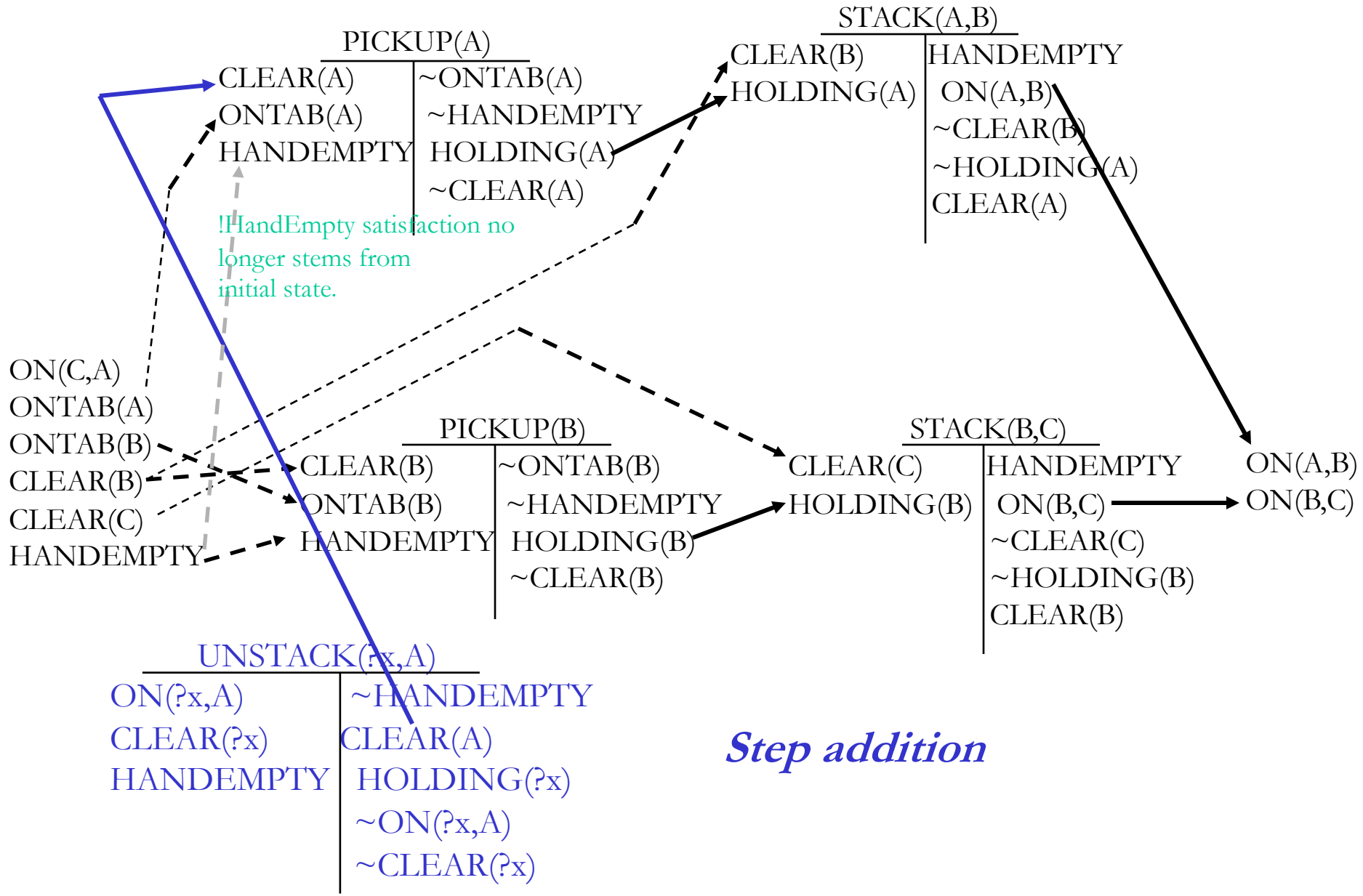
Step addition and tentative establishment

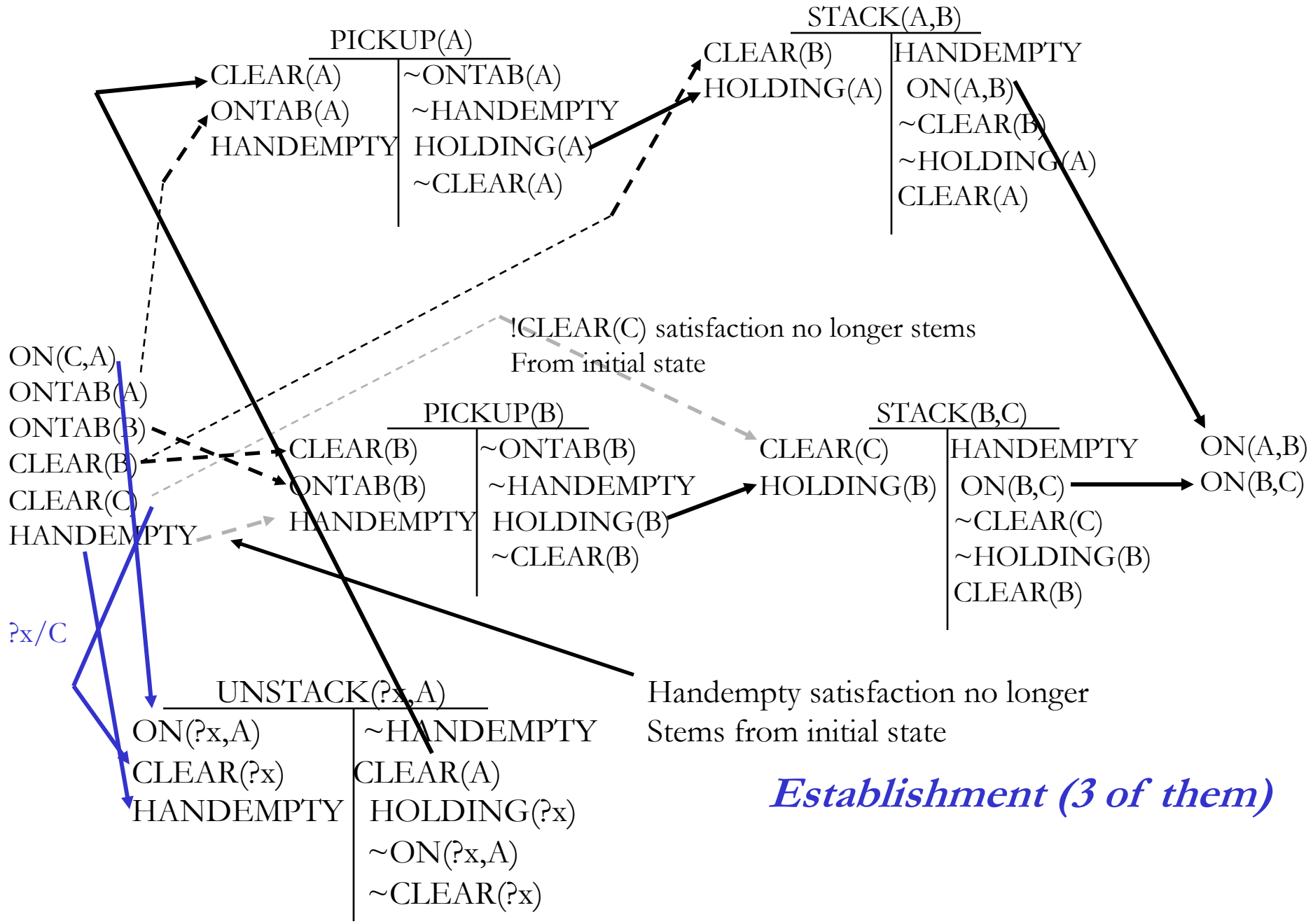
First Order Planning

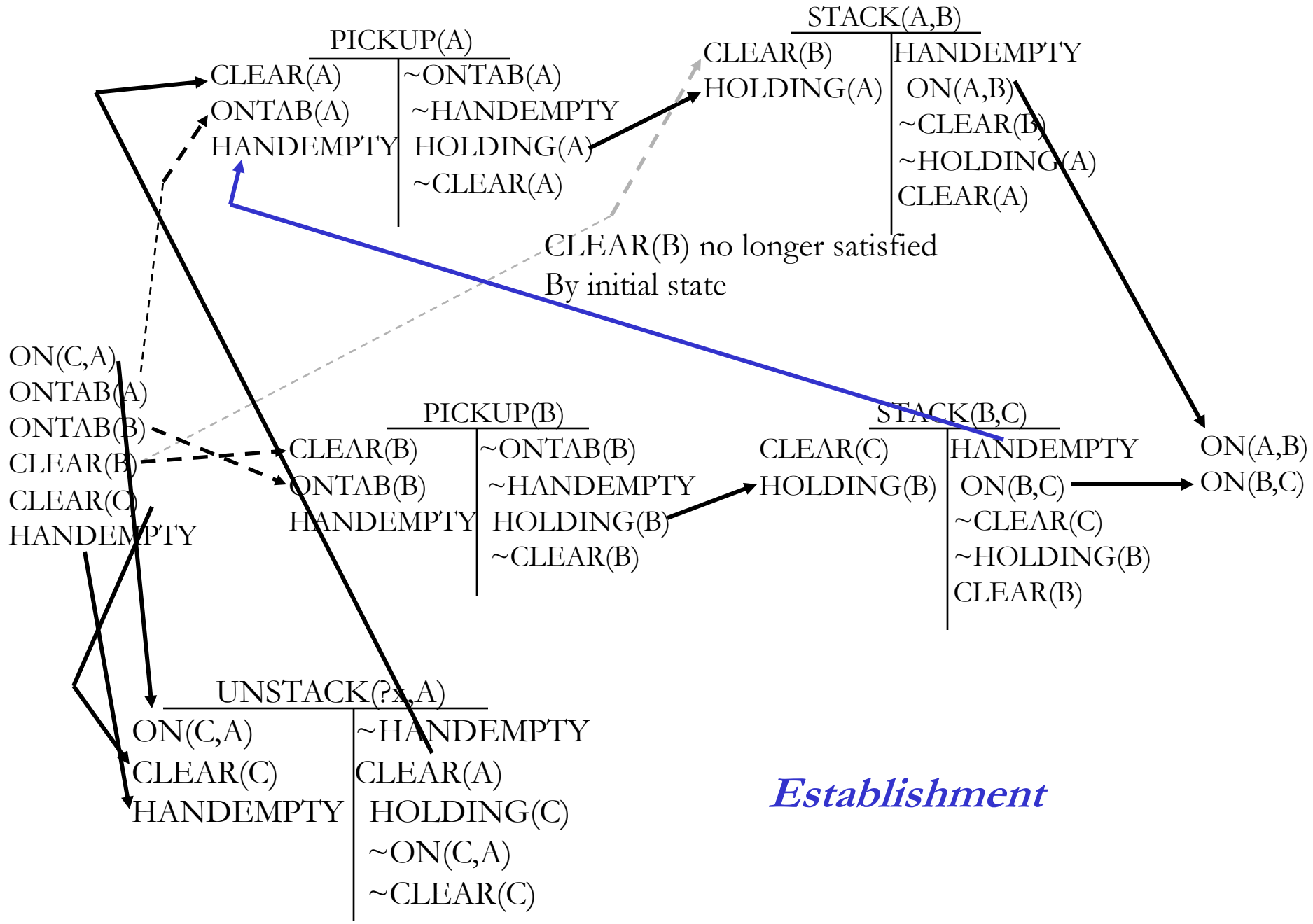


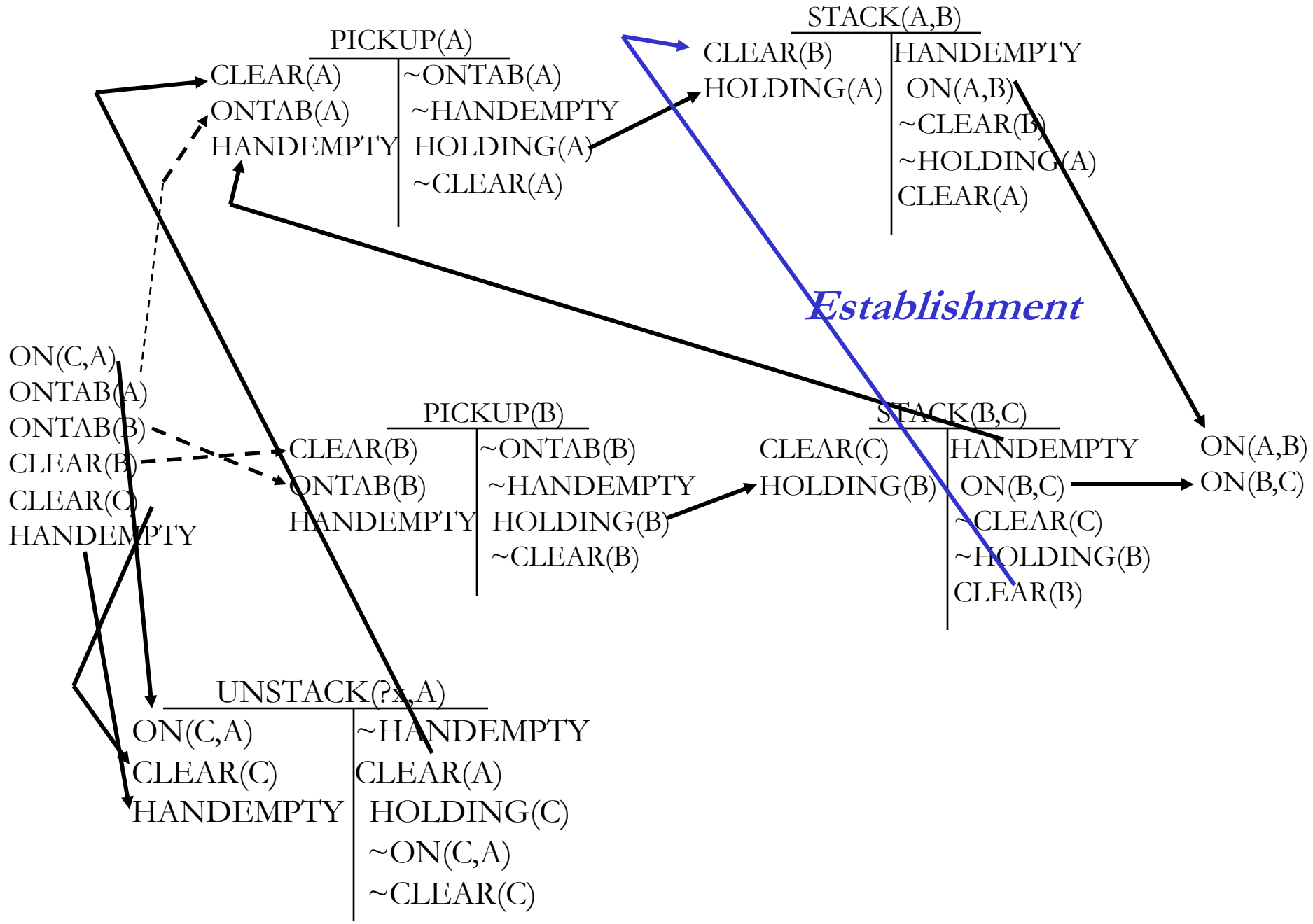
Step addition and tentative establishment

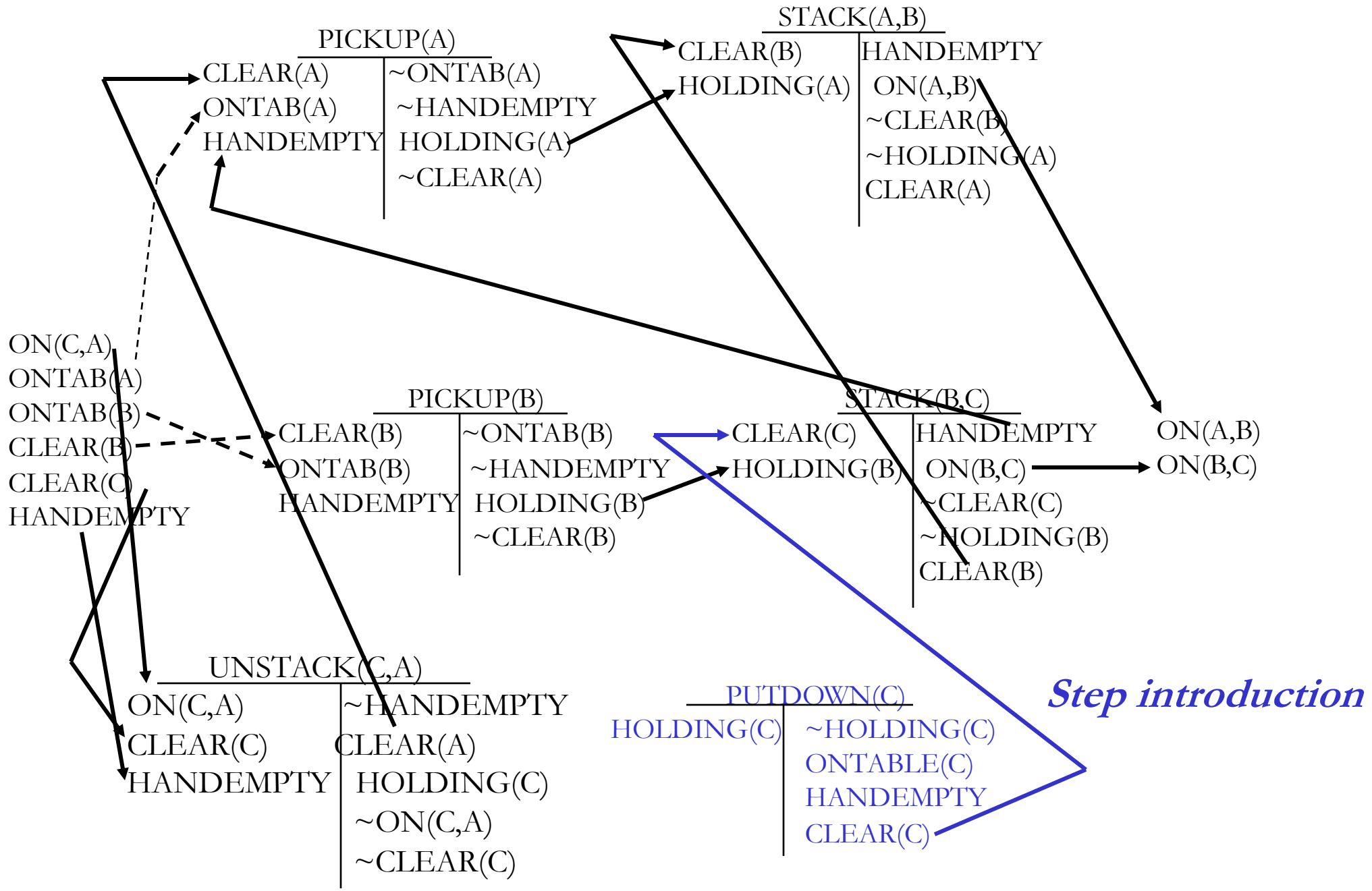
First Order Planning

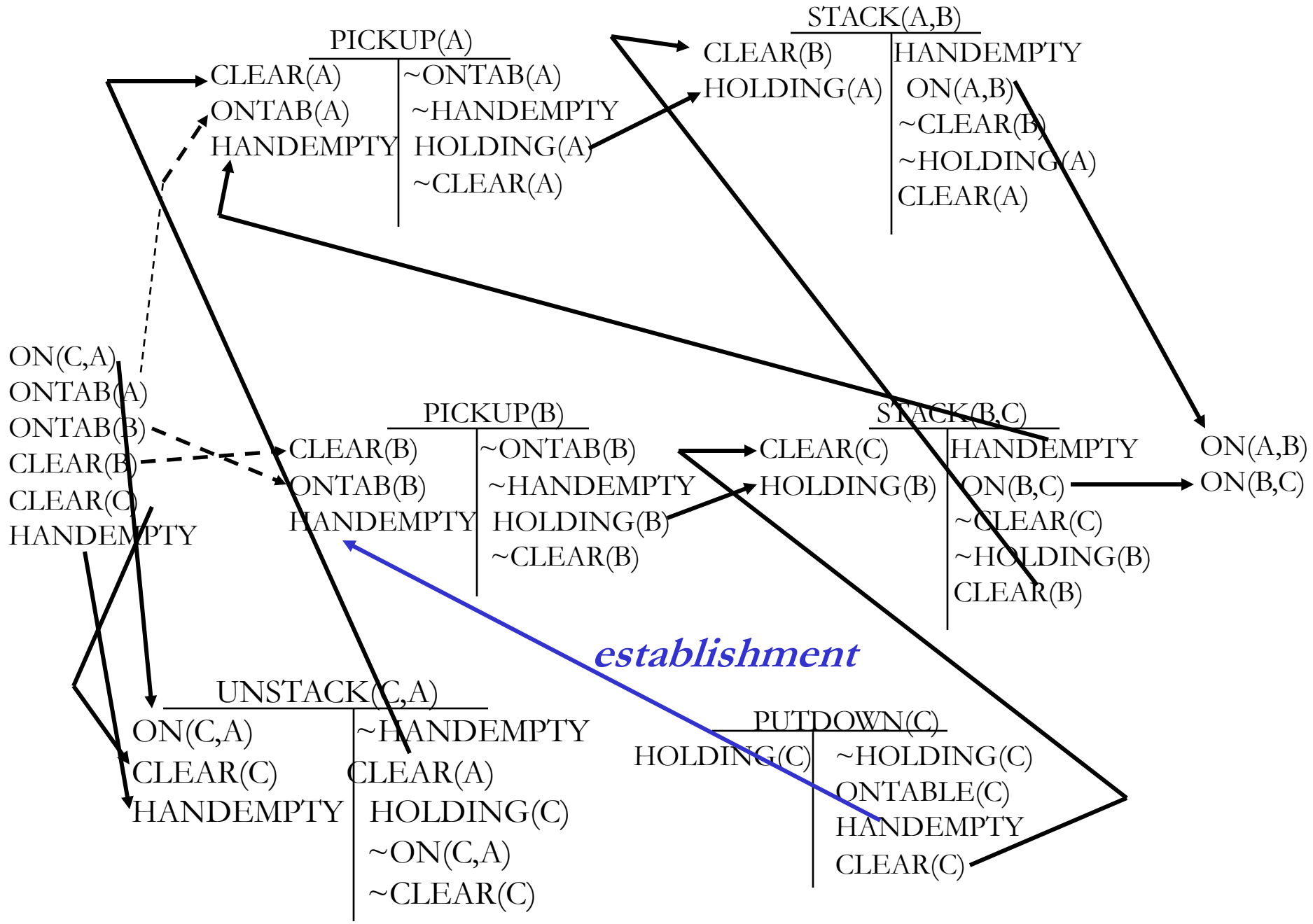


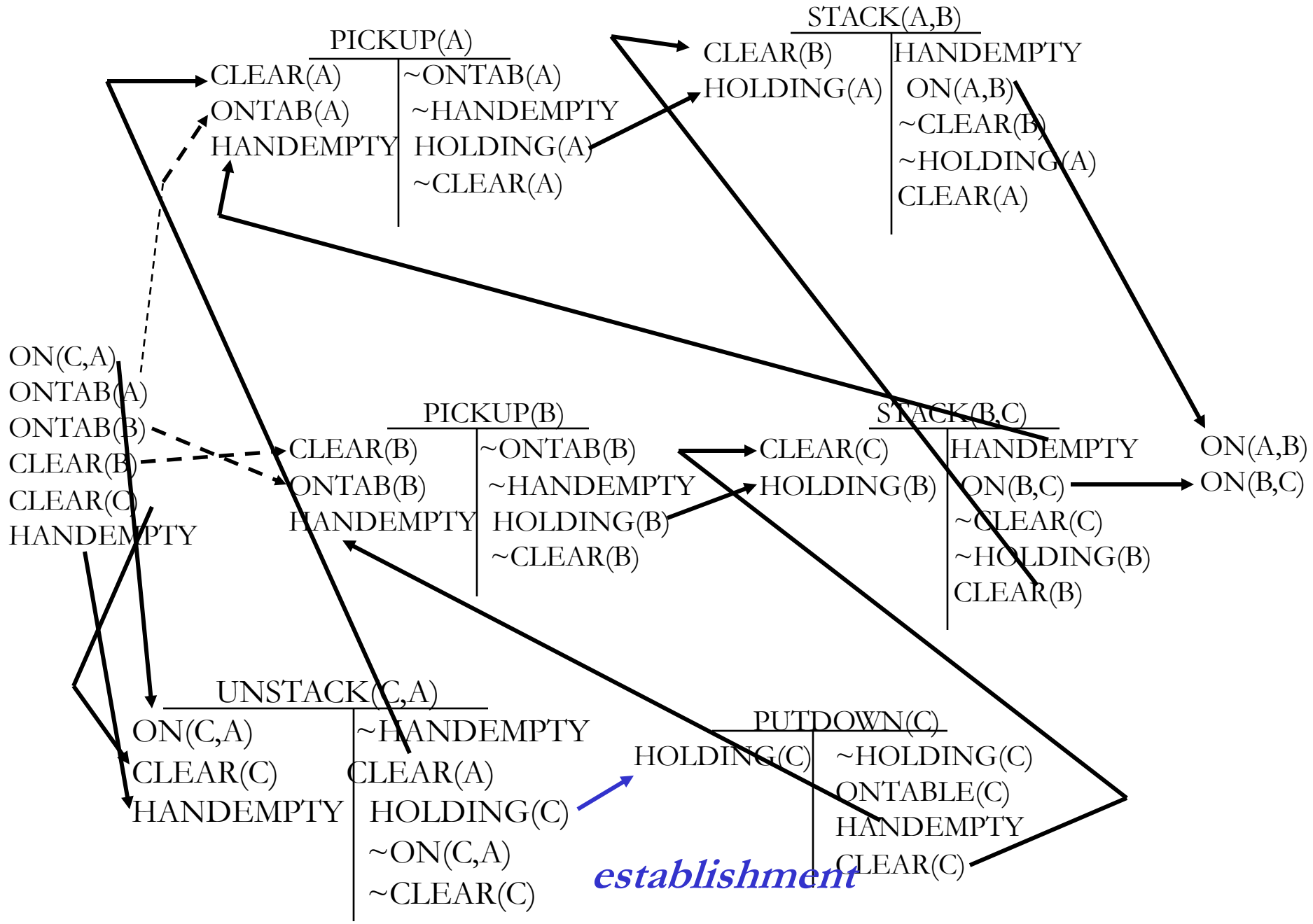

PICKUP(A)
CLEAR(A)
ONTAB(A)
HANDEMPTY
~ONTAB(A)
~HANDEMPTY
HOLDING(A)
~CLEAR(A)
STACK(A,B)
CLEAR(B)
HOLDING(A)
HANDEMPTY
ON(A,B)
~CLEAR(B)
~HOLDING(A)
CLEAR(A)
!CLEAR(C) satisfaction no longer stems
From initial state
ON(C,A)
ONTAB(A)
ONTAB(B)
CLEAR(B)
CLEAR(C)
HANDEMPTY
PICKUP(B)
CLEAR(B)
ONTAB(B)
HANDEMPTY
~ONTAB(B)
~HANDEMPTY
HOLDING(B)
~CLEAR(B)
STACK(B,C)
CLEAR(C)
HOLDING(B)
HANDEMPTY
ON(B,C)
~CLEAR(C)
~HOLDING(B)
CLEAR(B)
ON(A,B)
ON(B,C)
?x/C
UNSTACK(?x,A)
ON(?x,A)
CLEAR(?x)
HANDEMPTY
~HANDEMPTY
CLEAR(A)
HOLDING(?x)
~ON(?x,A)
~CLEAR(?x)
Handempty satisfaction no longer
Stems from initial state
Establishment (3 of them)


PICKUP(A)
CLEAR(A)
ONTAB(A)
HANDEMPTY
~ONTAB(A)
~HANDEMPTY
HOLDING(A)
~CLEAR(A)
STACK(A,B)
CLEAR(B)
HOLDING(A)
HANDEMPTY
ON(A,B)
~CLEAR(B)
~HOLDING(A)
CLEAR(A)
CLEAR(B) no longer satisfied
By initial state
ON(C,A)
ONTAB(A)
ONTAB(B)
CLEAR(B)
CLEAR(C)
HANDEMPTY
PICKUP(B)
CLEAR(B)
ONTAB(B)
HANDEMPTY
~ONTAB(B)
~HANDEMPTY
HOLDING(B)
~CLEAR(B)
STACK(B,C)
CLEAR(C)
HOLDING(B)
HANDEMPTY
ON(B,C)
~CLEAR(C)
~HOLDING(B)
CLEAR(B)
ON(A,B)
ON(B,C)
UNSTACK(?x,A)
ON(C,A)
CLEAR(C)
HANDEMPTY
~HANDEMPTY
CLEAR(A)
HOLDING(C)
~ON(C,A)
~CLEAR(C)
Establishment

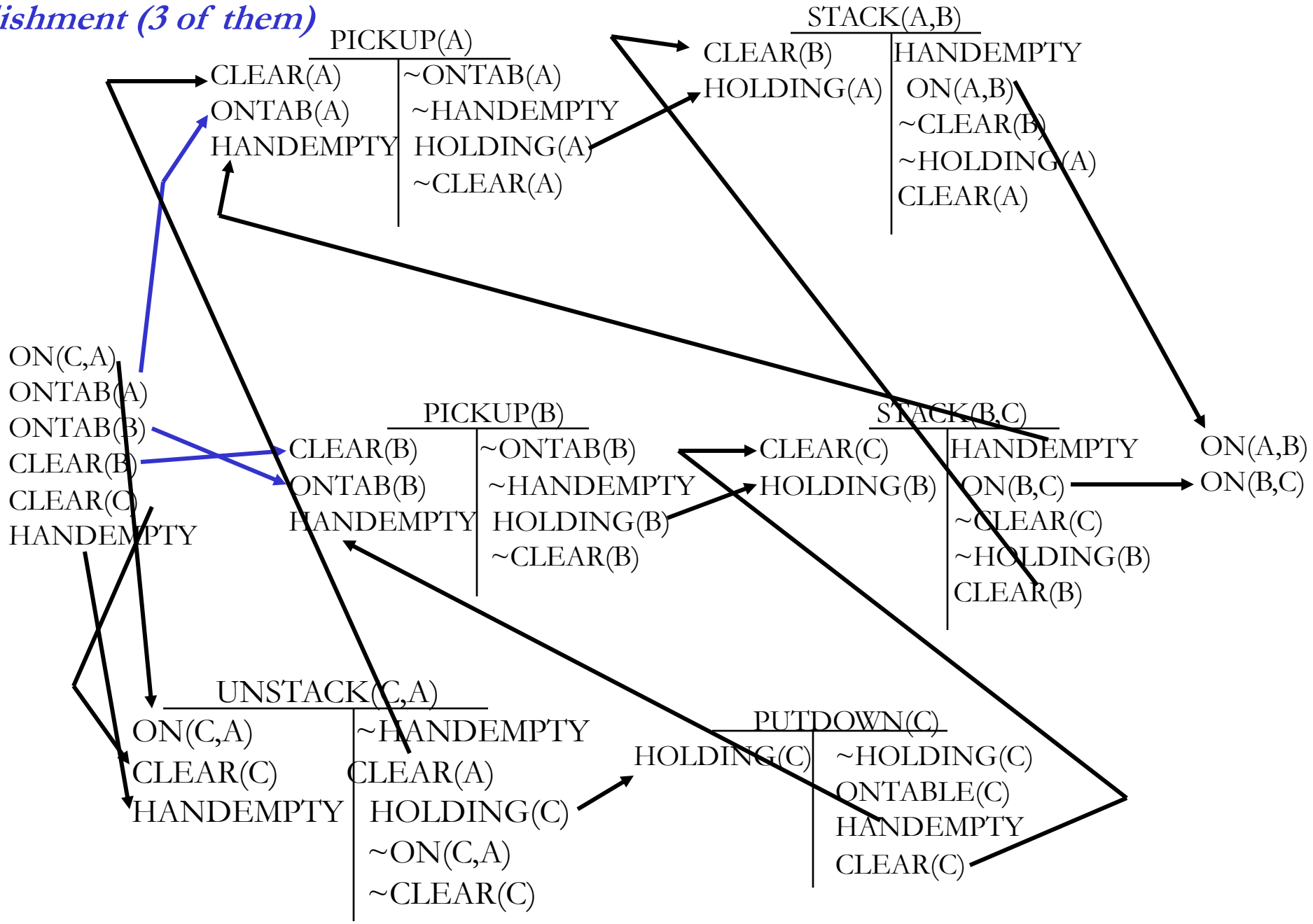

PICKUP(A)
CLEAR(A)
ONTAB(A)
HANDEMPTY
~ONTAB(A)
~HANDEMPTY
HOLDING(A)
~CLEAR(A)
STACK(A,B)
CLEAR(B)
HOLDING(A)
HANDEMPTY
ON(A,B)
~CLEAR(B)
~HOLDING(A)
CLEAR(A)
Establishment
ON(C,A)
ONTAB(A)
ONTAB(B)
CLEAR(B)
CLEAR(C)
HANDEMPTY
PICKUP(B)
CLEAR(B)
ONTAB(B)
HANDEMPTY
~ONTAB(B)
~HANDEMPTY
HOLDING(B)
~CLEAR(B)
STACK(B,C)
CLEAR(C)
HOLDING(B)
HANDEMPTY
ON(B,C)
~CLEAR(C)
~HOLDING(B)
CLEAR(B)
ON(A,B)
ON(B,C)
UNSTACK(?x,A)
ON(C,A)
CLEAR(C)
HANDEMPTY
~HANDEMPTY
CLEAR(A)
HOLDING(C)
~ON(C,A)
~CLEAR(C)


PICKUP(A)
CLEAR(A)
ONTAB(A)
HANDEMPTY
~ONTAB(A)
~HANDEMPTY
HOLDING(A)
~CLEAR(A)
STACK(A,B)
CLEAR(B)
HOLDING(A)
HANDEMPTY
ON(A,B)
~CLEAR(B)
~HOLDING(A)
CLEAR(A)
ON(C,A)
ONTAB(A)
ONTAB(B)
CLEAR(B)
CLEAR(C)
HANDEMPTY
PICKUP(B)
CLEAR(B)
ONTAB(B)
HANDEMPTY
~ONTAB(B)
~HANDEMPTY
HOLDING(B)
~CLEAR(B)
STACK(B,C)
CLEAR(C)
HOLDING(B)
HANDEMPTY
ON(B,C)
~CLEAR(C)
~HOLDING(B)
CLEAR(B)
ON(A,B)
ON(B,C)
UNSTACK(C,A)
ON(C,A)
CLEAR(C)
HANDEMPTY
~HANDEMPTY
CLEAR(A)
HOLDING(C)
~ON(C,A)
~CLEAR(C)
PUTDOWN(C)
HOLDING(C)
~HOLDING(C)
ONTABLE(C)
HANDEMPTY
CLEAR(C)
Step introduction

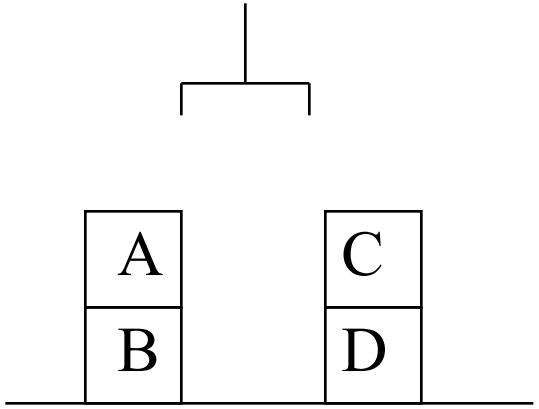

PICKUP(A)
CLEAR(A)
ONTAB(A)
HANDEMPTY
~ONTAB(A)
~HANDEMPTY
HOLDING(A)
~CLEAR(A)
STACK(A,B)
CLEAR(B)
HOLDING(A)
HANDEMPTY
ON(A,B)
~CLEAR(B)
~HOLDING(A)
CLEAR(A)
ON(C,A)
ONTAB(A)
ONTAB(B)
CLEAR(B)
CLEAR(C)
HANDEMPTY
PICKUP(B)
CLEAR(B)
ONTAB(B)
HANDEMPTY
~ONTAB(B)
~HANDEMPTY
HOLDING(B)
~CLEAR(B)
STACK(B,C)
CLEAR(C)
HOLDING(B)
HANDEMPTY
ON(B,C)
~CLEAR(C)
~HOLDING(B)
CLEAR(B)
ON(A,B)
ON(B,C)
establishment
UNSTACK(C,A)
ON(C,A)
CLEAR(C)
HANDEMPTY
~HANDEMPTY
CLEAR(A)
HOLDING(C)
~ON(C,A)
~CLEAR(C)
PUTDOWN(C)
HOLDING(C)
~HOLDING(C)
ONTABLE(C)
HANDEMPTY
CLEAR(C)


PICKUP(A)
CLEAR(A)
ONTAB(A)
HANDEMPTY
~ONTAB(A)
~HANDEMPTY
HOLDING(A)
~CLEAR(A)
STACK(A,B)
CLEAR(B)
HOLDING(A)
HANDEMPTY
ON(A,B)
~CLEAR(B)
~HOLDING(A)
CLEAR(A)
ON(C,A)
ONTAB(A)
ONTAB(B)
CLEAR(B)
CLEAR(C)
HANDEMPTY
PICKUP(B)
CLEAR(B)
ONTAB(B)
HANDEMPTY
~ONTAB(B)
~HANDEMPTY
HOLDING(B)
~CLEAR(B)
STACK(B,C)
CLEAR(C)
HOLDING(B)
HANDEMPTY
ON(B,C)
~CLEAR(C)
~HOLDING(B)
CLEAR(B)
ON(A,B)
ON(B,C)
UNSTACK(C,A)
ON(C,A)
CLEAR(C)
HANDEMPTY
~HANDEMPTY
CLEAR(A)
HOLDING(C)
~ON(C,A)
~CLEAR(C)
PUTDOWN(C)
HOLDING(C)
~HOLDING(C)
ONTABLE(C)
HANDEMPTY
CLEAR(C)
establishment

Establishment (3 of them)

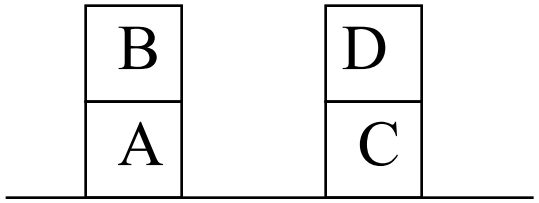


First Order Planning



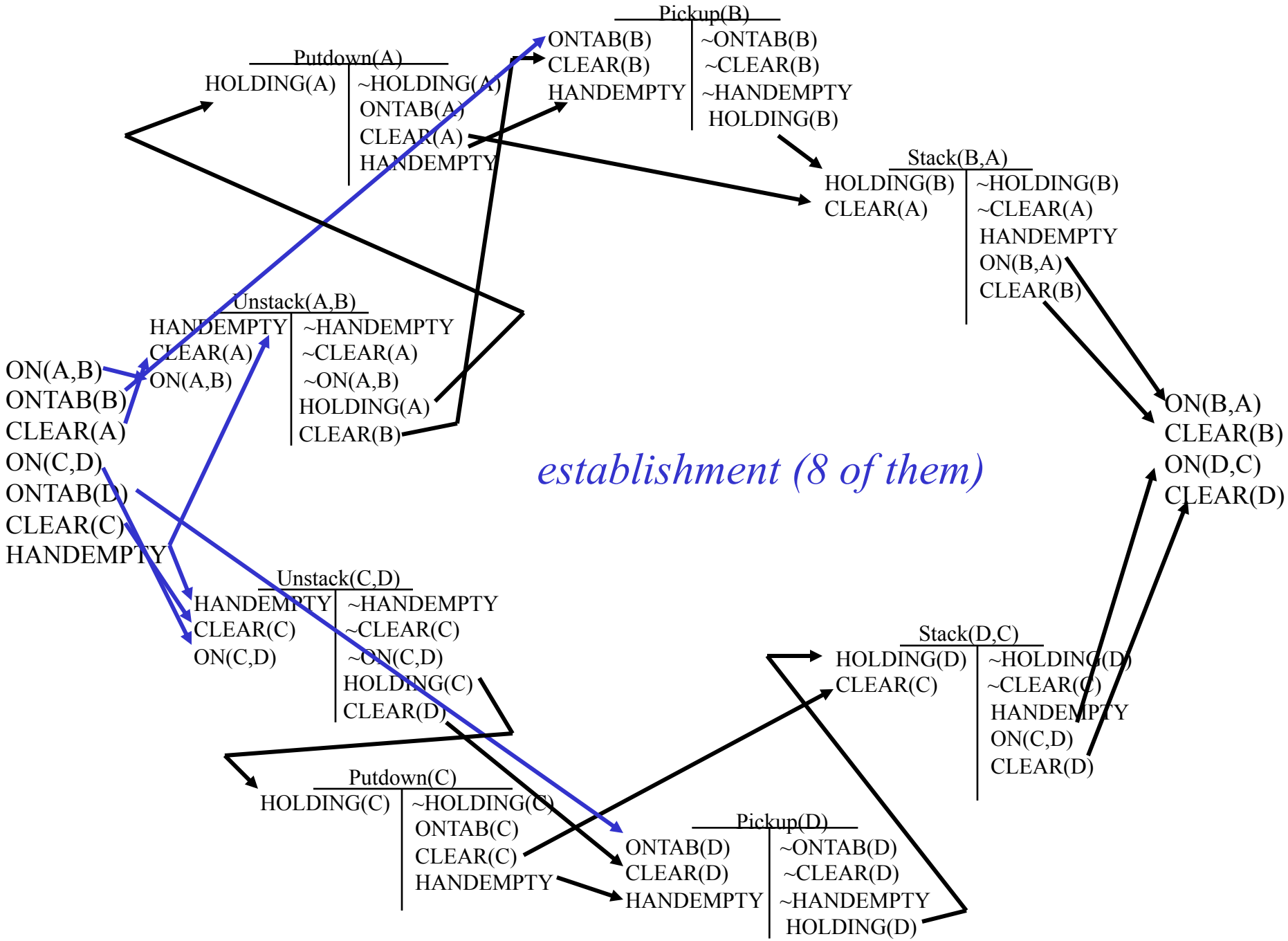
Initial State

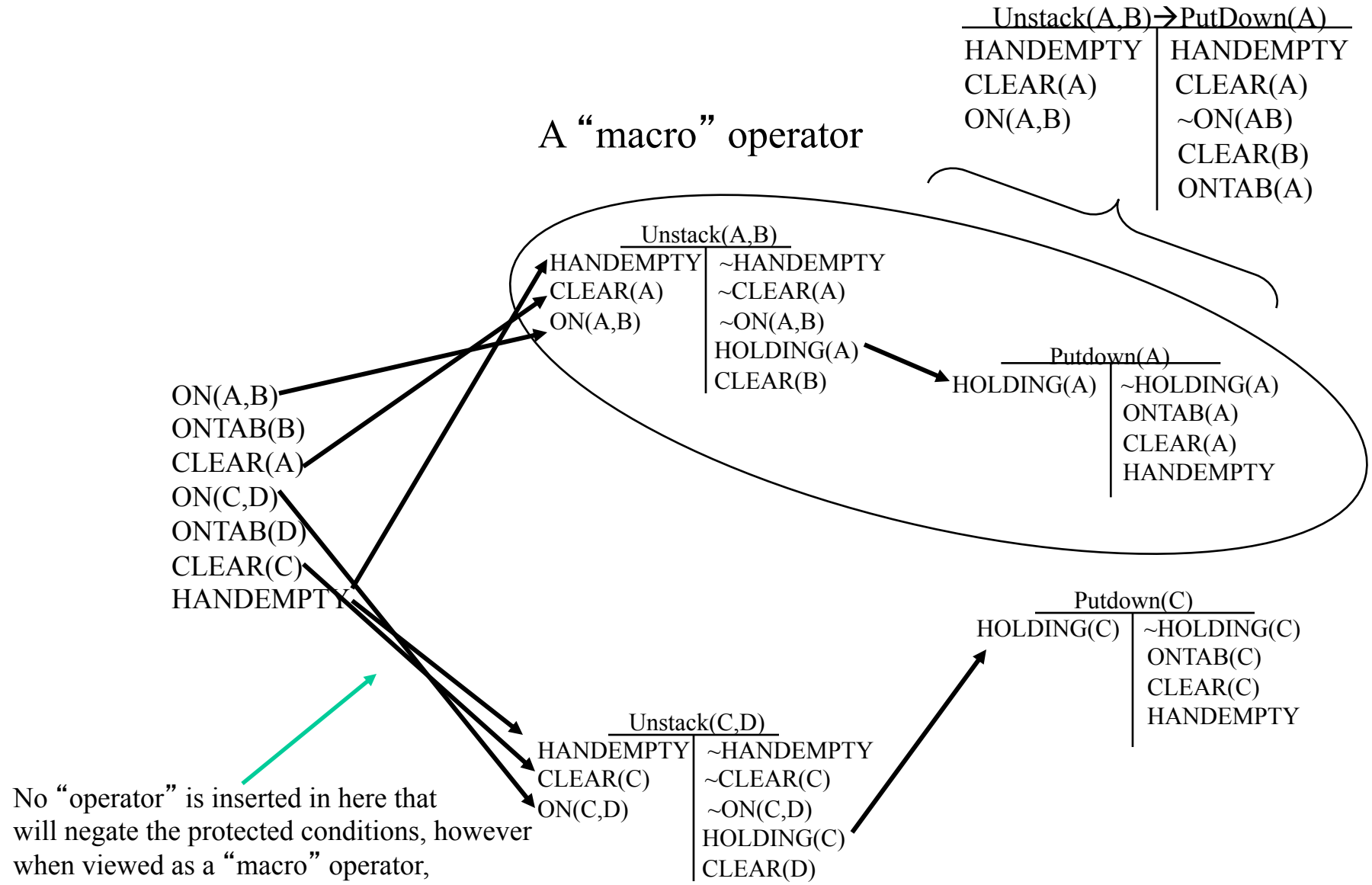
ON(A,B)
ONTAB(B)
CLEAR(A)
ON(C,D)
ONTAB(D)
CLEAR(C)
HANDEMPTY



Goal spec

ON(B,A)
CLEAR(B)
ON(D,C)
CLEAR(D)


Pickup(B)
ONTAB(B)
CLEAR(B)
HANDEMPTY
~ONTAB(B)
~CLEAR(B)
~HANDEMPTY
HOLDING(B)
Putdown(A)
HOLDING(A)
~HOLDING(A)
ONTAB(A)
CLEAR(A)
HANDEMPTY
Stack(B,A)
HOLDING(B)
CLEAR(A)
~HOLDING(B)
~CLEAR(A)
HANDEMPTY
ON(B,A)
CLEAR(B)
Unstack(A,B)
HANDEMPTY
CLEAR(A)
ON(A,B)
~HANDEMPTY
~CLEAR(A)
~ON(A,B)
HOLDING(A)
CLEAR(B)
ON(A,B)
ONTAB(B)
CLEAR(A)
ON(C,D)
ONTAB(D)
CLEAR(C)
HANDEMPTY
establishment (8 of them)
ON(B,A)
CLEAR(B)
ON(D,C)
CLEAR(D)
Unstack(C,D)
HANDEMPTY
CLEAR(C)
ON(C,D)
~HANDEMPTY
~CLEAR(C)
~ON(C,D)
HOLDING(C)
CLEAR(D)
Stack(D,C)
HOLDING(D)
CLEAR(C)
~HOLDING(D)
~CLEAR(C)
HANDEMPTY
ON(C,D)
CLEAR(D)
Putdown(C)
HOLDING(C)
~HOLDING(C)
ONTAB(C)
CLEAR(C)
HANDEMPTY
Pickup(D)
ONTAB(D)
CLEAR(D)
HANDEMPTY
~ONTAB(D)
~CLEAR(D)
~HANDEMPTY
HOLDING(D)

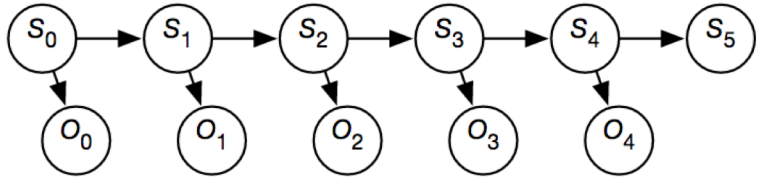

Unstack(A,B)→PutDown(A)
HANDEMPTY
CLEAR(A)
ON(A,B)
HANDEMPTY
CLEAR(A)
~ON(AB)
CLEAR(B)
ONTAB(A)
A "macro" operator
Unstack(A,B)
HANDEMPTY
CLEAR(A)
ON(A,B)
~HANDEMPTY
~CLEAR(A)
~ON(A,B)
HOLDING(A)
CLEAR(B)
Putdown(A)
HOLDING(A)
~HOLDING(A)
ONTAB(A)
CLEAR(A)
HANDEMPTY
ON(A,B)
ONTAB(B)
CLEAR(A)
ON(C,D)
ONTAB(D)
CLEAR(C)
HANDEMPTY
Putdown(C)
HOLDING(C)
~HOLDING(C)
ONTAB(C)
CLEAR(C)
HANDEMPTY
Unstack(C,D)
HANDEMPTY
CLEAR(C)
ON(C,D)
~HANDEMPTY
~CLEAR(C)
~ON(C,D)
HOLDING(C)
CLEAR(D)
No "operator" is inserted in here that will negate the protected conditions, however when viewed as a "macro" operator, Unstack(A,B)→PutDown(A) does not clobber any protected subgoals (or more exactly, it restores any subgoals (e.g., handempty) that are temporally "clobbered")

Hidden Markov Models

"A hidden Markov model (HMM) is an augmentation of a **Markov chain to include observations**. A hidden Markov model includes the state transition of the Markov chain, and adds to it observations at each time that depend on the state at the time." (David Poole and Alan Mackworth, "Artificial Intelligence: foundations of computational agents", 2nd edition, Cambridge University Press, 2017 https://artint.info/2e/html/ArtInt2e.Ch8.S5.SS2.html)

Hidden Markov Model

- A Hidden Markov Model (HMM) is a belief network:



The probabilities that need to be specified:

- $P(S_0)$ specifies initial conditions
- $P(S_{i+1} \mid S_i)$ specifies the dynamics
- $P(O_i \mid S_i)$ specifies the sensor model

Adapted with Slide 56 Chapter 8, Lecture 5 (https://artint.info/2e/slides/ch08/lect5.pdf) of Slides for David Poole and Alan Mackworth, "Artificial Intelligence: foundations of computational agents", 2nd

Hidden Markov Models

"An HMM is a temporal probabilistic model is which the state of the process is described by a single, discrete random variable. The possible values of the variable are the possible states of the world." (p. 473 of S. Russell and P. Norvig "Artificial Intelligence: A Modern Approach", 2021).

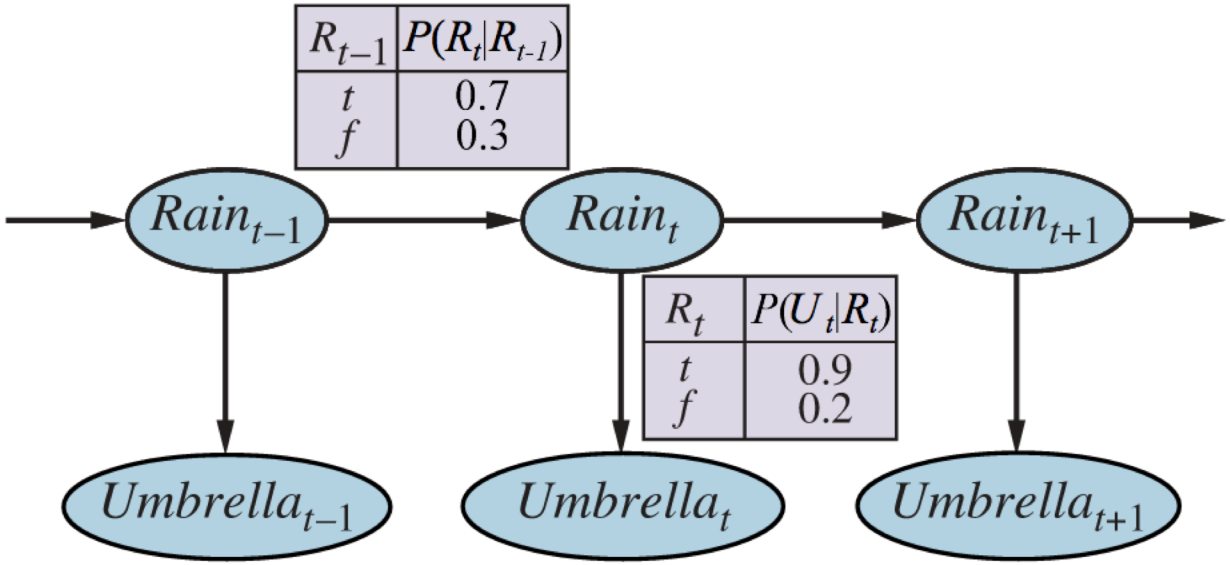


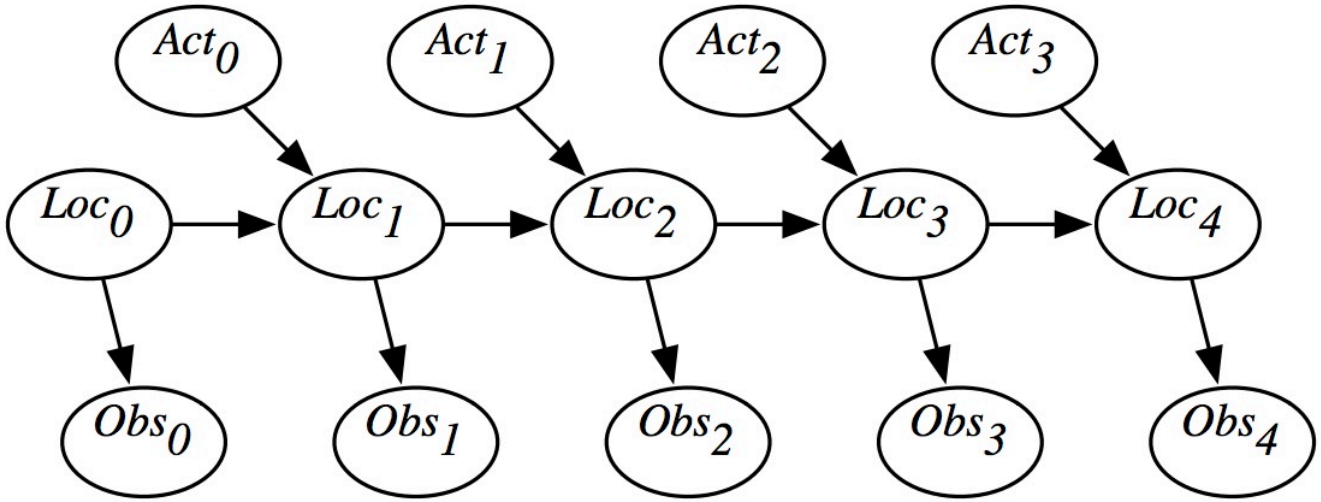
Figure 14.2 Bayesian network structure and conditional distributions describing the umbrella world. The transition model is $\mathbf{P}(Rain_t \mid Rain_{t-1})$ and the sensor model is $\mathbf{P}(Umbrella_t \mid Rain_t)$.

From S. Russell and P. Norvig "Artificial Intelligence: A Modern Approach" (2021). Retrieved from http://aima.cs.berkeley.edu/figures.pdf (slide 102). Used with permission.

Hidden Markov Models

HMMs augmented with actions, like planning operators, though with probabilistically qualified effects

- Suppose a robot wants to determine its location based on its actions and its sensor readings: Localization
- This can be represented by the augmented HMM:



Adapted with Slide 63 Chapter 8, Lecture 5 (https://artint.info/2e/slides/ch08/lect5.pdf) of Slides for David Poole and Alan Mackworth, "Artificial Intelligence: foundations of computational agents", 2nd edition, Cambridge University Press, 2017.