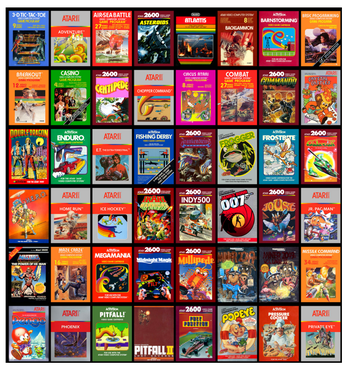

Classical Planning with Simulators: Results on the Atari Video Games

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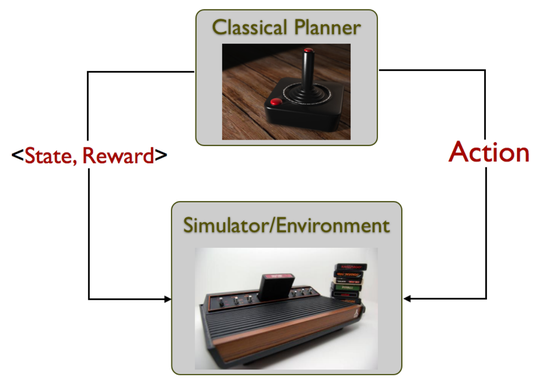
Arcade Learning Environment (U. of Alberta)

Specs of Environment/Simulator:

- RAM: 128 Bytes
- Screen: 160 x 210 pixels with (7 bit) 128-colour palette
- Joystick: 18 actions available
- 60 frames per second. Agents choose action every 5 frames (0.08 sec) of gameplay



ALE and Classical Planning

→ Classical Planning is about achivieng goals in deterministic systems with a fully known initial state

→ Problems represented in compact, logical form with PDDL

Planning setting in ALE is deterministic and initial state fully known

Yet classical planners can't be used!

- no PDDL encoding, i.e. No action model available
- no goals but rewards

→ *Bellemare et al.* consider Breadth-first Search (*BrFS*) and *MCTS*

→ Still, some recent "classical" planning algorithms can be applied almost off-the-shelf (Lipovetzky and Geffner 2012)

A Simple Pruned Breadth-First Search Algorithm

Definition (Novelty): **smallest** new tuple of atoms generated by a state, that no other state in the search **made true before**. $novelty : s \mapsto \mathbb{N}$

- $IW(i)$ = **breadth-first** search that **prunes** newly generated states whose $novelty(s) > i$.
- IW is a **sequence of calls** $IW(i)$ for $i = 0, 1, 2, \ldots$ over problem P until problem solved or i exceeds number of vars in problem

Key theoretical property: *IW* solves P in time $O(n^i)$ if $\boldsymbol{width(P) = i}$; $IW(i)$ then solves P **optimally** (Notion of width defined by Lipovetzky and Geffner 2012)

Experiments in a nutshell: *IW*, while simple and blind, **great algorithm** when goals restricted to **single atoms**. For **multiple atomic goals**, simple serialized version *IW* suffices, achiving **atomic goals one at a time**

IW in the Atari Games

→ *IW*(1) used with the 128 state variables (RAM 8-bit word) of 256 values each

→ *IW*(1) generates then up to $128 \times 256 \times 18$ (i.e, $589,824$) states

- Children in *IW*(1) generated in random order
- Discount factor used $\gamma = 0.995$

→ Action leading to most rewarding *IW*(1)-path is executed

IW is a purely exploration algorithm that does not take into account the accumulated reward for selecting the states to consider

Balancing Exploration and Exploitation

As a simple variant that combines exploration and exploitation, we evaluated a best-first search algorithm with two queues (2BFS)

- Queue 1: ordered first by novelty measure
- Queue 2: ordered by accumulated reward

→ 2BFS alternates between the two queues (similar technique used in LAMA planner)

→ When node expanded, its children are placed on both queues, with the exception of nodes with no accumulated reward, placed only in queue 1

Experimental Results

Same setting from Bellemare et al:

- Games are played for 5 minutes maximum (18,000 frames)
- 2BFS and *IW* have a maximum lookahead budget of $150,000$ simulated frames
- UCT has same budget by running 500 rollouts of depth 300
- Score is averaged among 5 runs per game

	IW(1)		2BFS		*BrFS*	UCT
Game	Score	Time	Score	Time	Score	Score
Alien	**25634**	81	12252	81	784	7785
Amidar	**1377**	28	1090	37	5	180
Assault	953	18	827	25	414	**1512**
Asterix	153400	24	77200	27	2136	**290700**
Asteroids	**51338**	66	22168	65	3127	4661
Atlantis	159420	13	154180	71	30460	**193858**
Bank Heist	**717**	39	362	64	22	498
Battle Zone	11600	86	**330800**	87	6313	70333
Beam Rider	9108	23	**9298**	29	694	6625
Berzerk	**2096**	58	802	73	195	554
Bowling	**69**	10	50	60	26	25
Boxing	**100**	15	**100**	22	**100**	**100**
Breakout	384	4	**772**	39	1	364
Carnival	**6372**	16	5516	53	950	5132
Centipede	99207	39	94236	67	**125123**	110422
Chopper Command	10980	76	27220	73	1827	**34019**
Crazy Climber	36160	4	36940	58	37110	**98172**
Demon Attack	20116	33	16025	41	443	**28159**
Double Dunk	-14	41	21	41	-19	**24**
Elevator Action	13480	26	10820	27	730	**18100**
Enduro	**500**	66	359	38	1	286
Fishing Derby	30	39	6	62	-92	**38**
Freeway	**31**	32	23	61	0	0
Frostbite	902	12	**2672**	38	137	271
Gopher	18256	19	15808	53	1019	**20560**
Gravitar	3920	62	**5980**	62	395	2850

Game	*IW*(1) Score	*IW*(1) Time	2BFS Score	2BFS Time	*BrFS* Score	UCT Score
Hero	**12985**	37	11524	69	1324	12860
Ice Hockey	**55**	89	49	89	-9	39
James Bond	**23070**	0	10080	30	25	330
Journey Escape	40080	38	**40600**	67	1327	7683
Kangaroo	**8760**	8	5320	31	90	1990
Krull	**6030**	28	4884	42	3089	5037
Kung Fu Master	**63780**	21	42180	43	12127	48855
Montezuma Revenge	0	14	**540**	39	0	0
Ms Pacman	21695	21	18927	23	1709	**22336**
Name This Game	9354	14	8304	25	5699	**15410**
Pong	**21**	17	**21**	35	-21	**21**
Pooyan	11225	8	10760	16	910	**17763**
Private Eye	-99	18	**2544**	44	58	100
Q*Bert	3705	11	11680	35	133	**17343**
Riverraid	**5694**	18	5062	37	2179	4449
Road Runner	**94940**	25	68500	41	245	38725
Robot Tank	**68**	34	52	34	2	50
Seaquest	**14272**	25	6138	33	288	5132
Space Invaders	2877	21	**3974**	34	112	2718
Star Gunner	1540	19	**4660**	18	1345	1207
Tennis	**24**	21	**24**	36	-24	3
Time Pilot	35000	9	36180	29	4064	**63855**
Tutankham	172	15	204	34	64	**226**
Up And Down	**110036**	12	54820	14	746	74474
Venture	**1200**	22	980	35	0	0
Video Pinball	**388712**	43	62075	43	55567	254748
Wizard Of Wor	**121060**	25	81500	27	3309	105500
Zaxxon	**29240**	34	15680	31	0	22610

	IW(1)	2BFS	*BrFS*	UCT
# Times Best (54 games)	26	13	1	19
# Times Better than *IW*	–	16	1	19
# Times Better than 2BFS	34	–	1	25
# Times Better than UCT	31	26	1	–

Search Tree Depths

- *BrFS* search tree results in a lookahead of 0.3 seconds
- *IW*(1) and 2BFS result in lookahead of up to 6–22 seconds

IW Planning vs. Google DeepMind learning (Nature 2015)

- lookahead/RAM state vs. reactive controller/Screen state
- Score-wise IW better than DeepMind in 45 out of 49 games

Wrap Up

→ *IW* makes use of the state structure (atoms) to order exploration

→ Exploitation of this structure pays off in classical planning and ALE

- Similar results reported for General Video Game Playing (GVG-AI) where games are stochastic (MDPS; IJCAI GIGA-2015 Workshop)

Key benefit of *IW* w.r.t. classical planning algorithms: Does not need compact PDDL-like encodings; it can work with simulators!