Observation, Communication and Intelligence in Agent-Based Systems

Nader Chmait David L. Dowe David G. Green
Yuan-Fang Li

{nader.chmait,david.dowe,david.green,yuanfang.li}@monash.edu
Faculty of Information Technology, Monash University,
Clayton, Australia

July 22-25, 2015

Presentation Outline

Problem description and goals

How do two factors affect *intelligence* in cooperative agent-based systems?

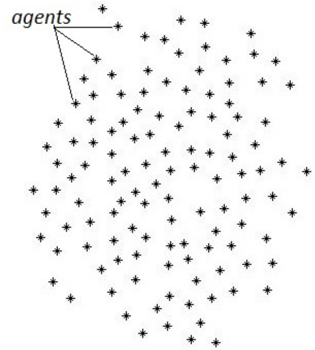
- Communication
- Observation

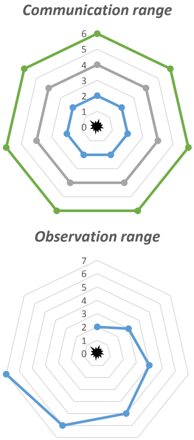
How do they depend on each other?

- and how does this reflect on the collective performance of the agents?

Problem description

Which factor has the greater influence?





Motivations

- to the best of our knowledge, no studies have applied formal intelligence tests for this purpose.
- in the real-world agents have limited sensitivity of the environment (observations)
- relying on communication to improve their performance can be inevitable.
- benefits of quantifying the influence
  - understanding the rules of information aggregation in a multiagent setting
  - predicting the usefulness and expected performance of these systems over different configurations.

Approach

- *Quantify* the performance of artificial agents.
  - Not every evaluation metric can be used as a formal (universal) intelligence test
- Use (machine) intelligence tests
  - evaluate a group of artificial agents collaborating in different settings
- Adjust communication and observation abilities
  - controlled experiments
  - how these changes are reflected by their measured intelligence

Presentation Outline

Methodology

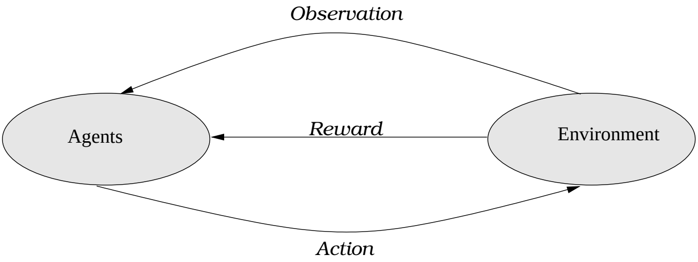
What: Anytime Universal Intelligence Test (anYnt)
Why :

- test derived from formal and mathematical considerations
- builds upon Legg and Hutter's definition of universal intelligence
- used in practice to evaluate artificial agents in a dynamic setting

How :

- agent-environment framework [4].
- controlled experiments
  1. Observation
  2. Communication

Agent-Environment Framework



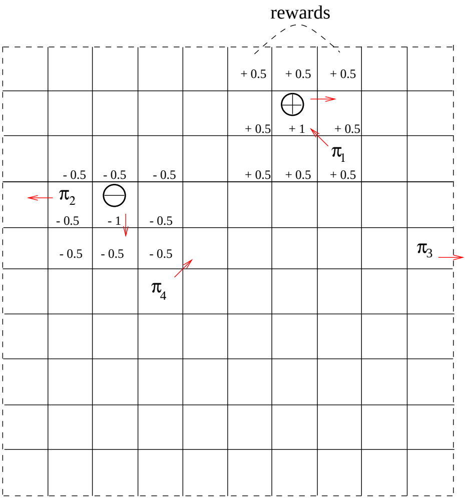
Λ (lambda) environment: Anytime Intelligence Test

An interactive setting:

- Set of agents $\Pi = \{\pi_1, \pi_2, \pi_3, \pi_4\}$
- $\oplus, \ominus$: positive/negative rewards
- Toroidal environment space
- Measured complexity of movement patterns
- Balanced environment
- Dynamic setting

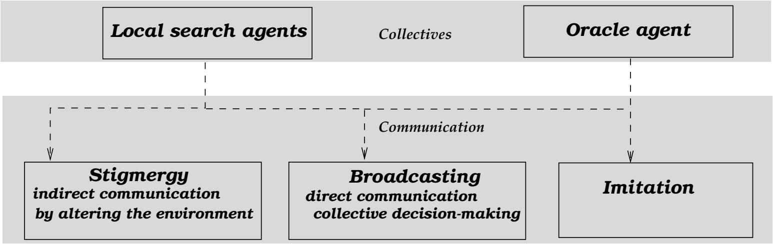
- Universal Intelligence [4]

$\Upsilon(\pi, U) := \sum_{\mu=i}^{\infty} p_U(\mu) \cdot V_\mu^\pi$
$= \sum_{\mu=i}^{\infty} p_U(\mu) \cdot E\left(\sum_{i=1}^{\infty} r_i^{\mu,\pi}\right)$
s.t. μ : environment coded on a universal machine U with probability $p_U(\mu)$



Communication modes

Set of agents $\Pi = \{\pi_1, \pi_2, \pi_3, \ldots, \pi_n\}$



Measuring Uncertainty and Information

Shannon's entropy [6]

- Environment μ with N possible states
- $\mathrm{H}(\mu)$: uncertainty in a given environment μ
- $\mathrm{H}(\mathrm{o})$: amount of information in an observation o
  - $\log_2$ the number of states in o, or the minimum number of bits needed to describe o
- $\mathrm{H}(\mathrm{c})$: amount of information in a communication range c
  - $\log_2$ the number of states in c, or the minimum number of bits needed to describe c

At the beginning of a test the entropy is maximal. Probability $p(s_\mu)$ of a given state s_μ occurring follows a uniform distribution and is equal to $1/|N|$.

$$\mathrm{H}(\mu) = -\sum_{s_\mu \in N} p(s_\mu) \log_2 p(s_\mu) = \log_2 |N| \text{ bits.}$$

Presentation Outline

Experiments

1. initialize Λ environment
   - set environment space dimensions
   - generate set of agents to be evaluated Π
   - initialize $\mathrm{H}(\mathrm{o})$ and $\mathrm{H}(\mathrm{c})$ parameters
2. evaluate Π over 1000 episodes
3. record average score $\Upsilon(\mathrm{H_o}, \mathrm{H_c}) \in [-1.0, 1.0]$ (used as intelligence/performance measure)
4. change entropy of $\mathrm{H}(\mathrm{o})$ *or* $\mathrm{H}(\mathrm{c})$
5. repeat experiment (from step 2) with new $\mathrm{H}(\mathrm{o})$ or $\mathrm{H}(\mathrm{c})$

Presentation Outline

Results: stigmergy or indirect communication

Observation entropies $H(o)$ $\longrightarrow$

Communication entropies $H(c)$ $\longrightarrow$

Indirect communication

$H(c)$ \ $H(o)$	0.04	0.11	0.22	0.36	0.54	0.76	1.01	1.30	1.62	1.99	2.38	2.82	3.29	3.79	4.33	4.91	5.53	6.18	6.86	7.58	8.34	9.14	9.97	10.84
10.84	0.0506	0.0693	0.0927	0.1120	0.1329	0.1517	0.1735	0.1998	0.2256	0.2545	0.2753	0.2903	0.3059	0.3277	0.3431	0.3615	0.3833	0.4076	0.4234	0.4328	0.4439	0.4470	0.4472	0.4470
9.97	0.0469	0.0646	0.0837	0.1078	0.1290	0.1502	0.1712	0.1978	0.2256	0.2667	0.2990	0.3179	0.3297	0.3422	0.3609	0.3778	0.3933	0.4140	0.4291	0.4385	0.4448	0.4475	0.4468	0.4473
9.14	0.0450	0.0657	0.0883	0.1008	0.1203	0.1434	0.1738	0.1950	0.2486	0.2907	0.3245	0.3419	0.3491	0.3652	0.3823	0.3930	0.4073	0.4213	0.4335	0.4398	0.4470	0.4472	0.4469	0.4465
8.34	0.0441	0.0618	0.0824	0.1022	0.1200	0.1409	0.1766	0.2188	0.2637	0.3064	0.3394	0.3588	0.3695	0.3779	0.3955	0.4059	0.4180	0.4273	0.4339	0.4458	0.4470	0.4459	0.4464	0.4468
7.58	0.0461	0.0702	0.0849	0.1046	0.1222	0.1497	0.1841	0.2333	0.2793	0.3249	0.3541	0.3707	0.3845	0.3945	0.4046	0.4131	0.4231	0.4311	0.4419	0.4450	0.4449	0.4466	0.4461	0.4471
6.86	0.0489	0.0677	0.0863	0.1056	0.1274	0.1584	0.2024	0.2542	0.3105	0.3445	0.3696	0.3828	0.3943	0.4005	0.4111	0.4202	0.4268	0.4389	0.4410	0.4448	0.4458	0.4465	0.4463	0.4467
6.18	0.0486	0.0671	0.0875	0.1076	0.1313	0.1676	0.2249	0.2817	0.3274	0.3575	0.3752	0.3897	0.4002	0.4079	0.4153	0.4229	0.4325	0.4383	0.4388	0.4409	0.4432	0.4438	0.4451	0.4468
5.53	0.0478	0.0720	0.0927	0.1139	0.1470	0.1853	0.2503	0.3062	0.3457	0.3669	0.3827	0.3969	0.4053	0.4119	0.4172	0.4284	0.4327	0.4318	0.4360	0.4362	0.4386	0.4404	0.4438	0.4467
4.91	0.0506	0.0721	0.0959	0.1199	0.1556	0.2088	0.2733	0.3255	0.3614	0.3770	0.3872	0.4016	0.4080	0.4141	0.4236	0.4295	0.4293	0.4306	0.4336	0.4353	0.4370	0.4408	0.4442	0.4468
4.33	0.0506	0.0701	0.0965	0.1268	0.1726	0.2388	0.3002	0.3446	0.3698	0.3875	0.3941	0.4053	0.4136	0.4202	0.4246	0.4255	0.4271	0.4294	0.4299	0.4300	0.4330	0.4395	0.4436	0.4471
3.79	0.0498	0.0745	0.1018	0.1413	0.1971	0.2685	0.3224	0.3579	0.3803	0.3893	0.3989	0.4073	0.4157	0.4187	0.4167	0.4197	0.4231	0.4227	0.4220	0.4249	0.4294	0.4373	0.4432	0.4469
3.29	0.0528	0.0741	0.1050	0.1534	0.2286	0.2955	0.3363	0.3670	0.3859	0.3960	0.4037	0.4103	0.4165	0.4138	0.4168	0.4179	0.4162	0.4171	0.4158	0.4182	0.4256	0.4344	0.4425	0.4470
2.82	0.0486	0.0790	0.1126	0.1686	0.2504	0.3151	0.3456	0.3732	0.3870	0.3982	0.4038	0.4132	0.4081	0.4109	0.4119	0.4135	0.4108	0.4071	0.4122	0.4128	0.4186	0.4308	0.4414	0.4464
2.38	0.0533	0.0809	0.1203	0.1881	0.2643	0.3216	0.3506	0.3770	0.3906	0.4011	0.4066	0.4046	0.4056	0.4054	0.4018	0.3999	0.4014	0.3987	0.4034	0.4102	0.4165	0.4279	0.4403	0.4463
1.99	0.0530	0.0836	0.1338	0.2069	0.2717	0.3202	0.3493	0.3731	0.3897	0.3976	0.3947	0.4017	0.4001	0.3958	0.3948	0.3917	0.3913	0.3956	0.3948	0.4023	0.4113	0.4285	0.4404	0.4465
1.62	0.0533	0.0898	0.1457	0.2127	0.2681	0.3125	0.3444	0.3705	0.3893	0.3902	0.3907	0.3919	0.3939	0.3867	0.3846	0.3856	0.3862	0.3843	0.3869	0.3990	0.4083	0.4269	0.4404	0.4461
1.30	0.0570	0.0929	0.1562	0.2140	0.2566	0.2991	0.3378	0.3690	0.3729	0.3830	0.3816	0.3879	0.3829	0.3784	0.3774	0.3800	0.3791	0.3811	0.3873	0.3899	0.4062	0.4238	0.4391	0.4469
1.01	0.0565	0.1033	0.1582	0.2100	0.2538	0.2894	0.3195	0.3447	0.3622	0.3741	0.3772	0.3811	0.3755	0.3741	0.3739	0.3752	0.3779	0.3805	0.3830	0.3926	0.4056	0.4247	0.4397	0.4468
0.76	0.0604	0.1051	0.1568	0.1969	0.2339	0.2635	0.2985	0.3269	0.3488	0.3615	0.3665	0.3693	0.3705	0.3718	0.3727	0.3745	0.3757	0.3811	0.3799	0.3886	0.4017	0.4243	0.4403	0.4467
0.54	0.0645	0.1002	0.1448	0.1849	0.2159	0.2478	0.2758	0.3061	0.3352	0.3500	0.3577	0.3635	0.3705	0.3736	0.3757	0.3771	0.3747	0.3794	0.3813	0.3890	0.4008	0.4220	0.4392	0.4468
0.36	0.0660	0.0956	0.1355	0.1637	0.1899	0.2197	0.2580	0.2882	0.3188	0.3381	0.3560	0.3650	0.3705	0.3741	0.3781	0.3798	0.3828	0.3873	0.3853	0.3899	0.4022	0.4216	0.4405	0.4467
0.22	0.0605	0.0917	0.1150	0.1514	0.1777	0.2061	0.2378	0.2714	0.3023	0.3317	0.3498	0.3643	0.3768	0.3797	0.3817	0.3877	0.3910	0.3916	0.3941	0.3958	0.4058	0.4231	0.4420	0.4472
0.11	0.0548	0.0779	0.0997	0.1313	0.1592	0.1893	0.2186	0.2520	0.2864	0.3165	0.3372	0.3630	0.3728	0.3845	0.3911	0.3952	0.4016	0.4032	0.4024	0.4090	0.4137	0.4274	0.4422	0.4469
0.04	0.0486	0.0676	0.0919	0.1146	0.1400	0.1715	0.2025	0.2317	0.2671	0.2987	0.3307	0.3542	0.3734	0.3890	0.3970	0.4031	0.4091	0.4116	0.4141	0.4194	0.4265	0.4305	0.4422	0.4464

Results: direct communication

Observation entropies $H(o)$ $\longrightarrow$

Communication entropies $H(c)$ $\longrightarrow$

Direct communication

$H(c)$ \ $H(o)$	0.04	0.11	0.22	0.36	0.54	0.76	1.01	1.30	1.62	1.99	2.38	2.82	3.29	3.79	4.33	4.91	5.53	6.18	6.86	7.58	8.34	9.14	9.97	10.84
10.84	0.3487	0.3843	0.4119	0.4271	0.4352	0.4424	0.4443	0.4454	0.4469	0.4470	0.4470	0.4470	0.4470	0.4470	0.4470	0.4470	0.4470	0.4470	0.4470	0.4470	0.4470	0.4470	0.4470	0.4470
9.97	0.3487	0.3843	0.4119	0.4271	0.4352	0.4424	0.4443	0.4454	0.4469	0.4470	0.4470	0.4470	0.4470	0.4470	0.4470	0.4470	0.4470	0.4470	0.4470	0.4470	0.4470	0.4470	0.4470	0.4470
9.14	0.3487	0.3843	0.4119	0.4271	0.4352	0.4424	0.4443	0.4454	0.4469	0.4470	0.4470	0.4470	0.4470	0.4470	0.4470	0.4470	0.4470	0.4470	0.4470	0.4470	0.4470	0.4470	0.4470	0.4470
8.34	0.3487	0.3843	0.4119	0.4271	0.4352	0.4424	0.4443	0.4454	0.4469	0.4470	0.4470	0.4470	0.4470	0.4470	0.4470	0.4470	0.4470	0.4470	0.4470	0.4470	0.4470	0.4470	0.4470	0.4470
7.58	0.3487	0.3843	0.4119	0.4271	0.4352	0.4424	0.4443	0.4454	0.4469	0.4470	0.4470	0.4470	0.4470	0.4470	0.4470	0.4470	0.4470	0.4470	0.4470	0.4470	0.4470	0.4470	0.4470	0.4470
6.86	0.3487	0.3843	0.4119	0.4271	0.4352	0.4424	0.4443	0.4454	0.4469	0.4470	0.4470	0.4470	0.4470	0.4470	0.4470	0.4470	0.4470	0.4470	0.4470	0.4470	0.4470	0.4470	0.4470	0.4470
6.18	0.3449	0.3799	0.4057	0.4208	0.4282	0.4364	0.4385	0.4400	0.4418	0.4416	0.4420	0.4429	0.4432	0.4440	0.4444	0.4447	0.4455	0.4462	0.4469	0.4469	0.4470	0.4469	0.4469	0.4470
5.53	0.3377	0.3698	0.3947	0.4120	0.4205	0.4290	0.4316	0.4326	0.4353	0.4356	0.4359	0.4378	0.4391	0.4403	0.4415	0.4422	0.4435	0.4452	0.4463	0.4465	0.4469	0.4470	0.4469	0.4469
4.91	0.3294	0.3588	0.3888	0.4028	0.4111	0.4191	0.4217	0.4241	0.4253	0.4277	0.4308	0.4321	0.4333	0.4367	0.4377	0.4398	0.4417	0.4437	0.4455	0.4464	0.4472	0.4470	0.4469	0.4468
4.33	0.3153	0.3557	0.3767	0.3901	0.4016	0.4079	0.4115	0.4156	0.4167	0.4193	0.4222	0.4269	0.4280	0.4311	0.4352	0.4365	0.4401	0.4418	0.4449	0.4461	0.4470	0.4469	0.4468	0.4468
3.79	0.3069	0.3415	0.3633	0.3801	0.3890	0.3976	0.4016	0.4046	0.4080	0.4125	0.4153	0.4183	0.4219	0.4264	0.4295	0.4350	0.4380	0.4407	0.4436	0.4460	0.4471	0.4471	0.4469	0.4471
3.29	0.3002	0.3349	0.3544	0.3709	0.3760	0.3844	0.3912	0.3942	0.3985	0.4023	0.4068	0.4100	0.4179	0.4216	0.4276	0.4326	0.4360	0.4407	0.4431	0.4458	0.4467	0.4470	0.4469	0.4471
2.82	0.2826	0.3124	0.3395	0.3561	0.3614	0.3732	0.3780	0.3822	0.3873	0.3944	0.3979	0.4047	0.4103	0.4163	0.4229	0.4306	0.4342	0.4390	0.4430	0.4458	0.4470	0.4470	0.4467	0.4469
2.38	0.2713	0.3035	0.3237	0.3433	0.3503	0.3590	0.3651	0.3716	0.3741	0.3829	0.3906	0.3965	0.4030	0.4113	0.4174	0.4259	0.4315	0.4383	0.4422	0.4454	0.4466	0.4475	0.4468	0.4468
1.99	0.2624	0.2916	0.3074	0.3278	0.3395	0.3483	0.3535	0.3588	0.3656	0.3713	0.3827	0.3898	0.3989	0.4032	0.4136	0.4241	0.4309	0.4375	0.4420	0.4454	0.4469	0.4472	0.4470	0.4468
1.62	0.2444	0.2764	0.2979	0.3130	0.3273	0.3341	0.3413	0.3507	0.3547	0.3640	0.3756	0.3830	0.3918	0.4025	0.4108	0.4212	0.4288	0.4358	0.4413	0.4444	0.4468	0.4471	0.4467	0.4468
1.30	0.2303	0.2669	0.2875	0.3060	0.3114	0.3237	0.3316	0.3365	0.3466	0.3548	0.3652	0.3765	0.3830	0.3951	0.4072	0.4140	0.4263	0.4357	0.4410	0.4451	0.4474	0.4472	0.4468	0.4468
1.01	0.2201	0.2494	0.2714	0.2913	0.2981	0.3104	0.3202	0.3285	0.3365	0.3434	0.3561	0.3671	0.3789	0.3905	0.4033	0.4158	0.4231	0.4338	0.4397	0.4442	0.4468	0.4475	0.4466	0.4469
0.76	0.2100	0.2408	0.2586	0.2780	0.2876	0.2969	0.3071	0.3184	0.3225	0.3362	0.3468	0.3627	0.3735	0.3849	0.3994	0.4098	0.4211	0.4311	0.4397	0.4445	0.4468	0.4475	0.4468	0.4470
0.54	0.1959	0.2220	0.2405	0.2616	0.2734	0.2800	0.2955	0.3037	0.3124	0.3251	0.3390	0.3536	0.3663	0.3825	0.3967	0.4108	0.4211	0.4304	0.4385	0.4447	0.4469	0.4476	0.4471	0.4467
0.36	0.1750	0.2062	0.2265	0.2386	0.2591	0.2728	0.2820	0.2909	0.3023	0.3170	0.3298	0.3484	0.3627	0.3768	0.3910	0.4050	0.4189	0.4283	0.4382	0.4432	0.4469	0.4477	0.4468	0.4469
0.22	0.1536	0.1798	0.2008	0.2240	0.2412	0.2551	0.2689	0.2824	0.2952	0.3089	0.3214	0.3379	0.3517	0.3732	0.3878	0.4045	0.4176	0.4267	0.4372	0.4428	0.4470	0.4473	0.4469	0.4466
0.11	0.1245	0.1577	0.1780	0.1981	0.2143	0.2311	0.2505	0.2646	0.2784	0.2950	0.3129	0.3314	0.3507	0.3665	0.3844	0.4005	0.4141	0.4290	0.4373	0.4434	0.4471	0.4476	0.4464	0.4470
0.04	0.0879	0.1194	0.1405	0.1642	0.1803	0.2043	0.2236	0.2455	0.2636	0.2847	0.3026	0.3240	0.3427	0.3635	0.3782	0.3971	0.4133	0.4273	0.4367	0.4435	0.4470	0.4478	0.4469	0.4463

Results: imitation

Observation entropies $H(o)$ $\longrightarrow$

Communication entropies $H(c)$ $\longrightarrow$

Imitation

$H(c)$ \ $H(o)$	0.04	0.11	0.22	0.36	0.54	0.76	1.01	1.30	1.62	1.99	2.38	2.82	3.29	3.79	4.33	4.91	5.53	6.18	6.86	7.58	8.34	9.14	9.97	10.84
10.84	0.7978	0.7978	0.7978	0.7978	0.7978	0.7978	0.7978	0.7978	0.7978	0.7978	0.7978	0.7978	0.7978	0.7978	0.7978	0.7978	0.7978	0.7978	0.7978	0.7978	0.7978	0.7978	0.7978	0.7978
9.97	0.7977	0.7977	0.7977	0.7978	0.7977	0.7978	0.7978	0.7978	0.7978	0.7977	0.7978	0.7978	0.7977	0.7977	0.7977	0.7977	0.7978	0.7977	0.7978	0.7978	0.7977	0.7977	0.7978	0.7978
9.14	0.7976	0.7976	0.7976	0.7977	0.7976	0.7977	0.7977	0.7976	0.7976	0.7977	0.7978	0.7977	0.7977	0.7977	0.7977	0.7977	0.7978	0.7978	0.7978	0.7978	0.7978	0.7978	0.7978	0.7978
8.34	0.7975	0.7975	0.7975	0.7976	0.7976	0.7976	0.7975	0.7976	0.7976	0.7976	0.7976	0.7976	0.7977	0.7977	0.7977	0.7976	0.7977	0.7978	0.7978	0.7978	0.7978	0.7977	0.7979	0.7978
7.58	0.7977	0.7975	0.7977	0.7975	0.7977	0.7974	0.7976	0.7976	0.7976	0.7975	0.7975	0.7977	0.7976	0.7977	0.7978	0.7978	0.7978	0.7979	0.7977	0.7979	0.7980	0.7978	0.7978	0.7978
6.86	0.7973	0.7976	0.7975	0.7974	0.7973	0.7973	0.7976	0.7975	0.7977	0.7976	0.7975	0.7976	0.7973	0.7976	0.7974	0.7978	0.7979	0.7979	0.7979	0.7980	0.7979	0.7979	0.7978	0.7979
6.18	0.7973	0.7971	0.7973	0.7969	0.7972	0.7971	0.7976	0.7973	0.7973	0.7974	0.7971	0.7973	0.7972	0.7976	0.7976	0.7976	0.7976	0.7976	0.7977	0.7980	0.7981	0.7978	0.7979	0.7979
5.53	0.7973	0.7972	0.7971	0.7976	0.7973	0.7971	0.7974	0.7974	0.7974	0.7975	0.7972	0.7975	0.7974	0.7972	0.7972	0.7979	0.7975	0.7979	0.7979	0.7976	0.7978	0.7978	0.7978	0.7979
4.91	0.7966	0.7964	0.7966	0.7966	0.7965	0.7968	0.7970	0.7972	0.7966	0.7970	0.7969	0.7967	0.7970	0.7975	0.7974	0.7974	0.7974	0.7978	0.7979	0.7976	0.7980	0.7978	0.7978	0.7979
4.33	0.7958	0.7961	0.7960	0.7960	0.7960	0.7962	0.7964	0.7964	0.7966	0.7968	0.7968	0.7968	0.7974	0.7975	0.7969	0.7978	0.7977	0.7977	0.7983	0.7981	0.7980	0.7982	0.7981	0.7981
3.79	0.7950	0.7956	0.7953	0.7956	0.7954	0.7955	0.7958	0.7955	0.7958	0.7963	0.7967	0.7960	0.7959	0.7972	0.7967	0.7970	0.7969	0.7970	0.7973	0.7976	0.7979	0.7982	0.7977	0.7979
3.29	0.7937	0.7952	0.7945	0.7947	0.7951	0.7938	0.7947	0.7949	0.7949	0.7957	0.7952	0.7949	0.7955	0.7966	0.7960	0.7962	0.7968	0.7972	0.7971	0.7979	0.7981	0.7979	0.7979	0.7979
2.82	0.7916	0.7913	0.7915	0.7931	0.7916	0.7922	0.7925	0.7934	0.7922	0.7944	0.7929	0.7943	0.7938	0.7955	0.7953	0.7954	0.7962	0.7962	0.7973	0.7970	0.7988	0.7976	0.7975	0.7976
2.38	0.7851	0.7834	0.7821	0.7846	0.7833	0.7856	0.7859	0.7849	0.7837	0.7852	0.7871	0.7895	0.7900	0.7900	0.7914	0.7937	0.7932	0.7948	0.7968	0.7971	0.7983	0.7976	0.7972	0.7975
1.99	0.7610	0.7593	0.7615	0.7633	0.7619	0.7593	0.7587	0.7654	0.7641	0.7618	0.7702	0.7655	0.7721	0.7737	0.7793	0.7815	0.7882	0.7918	0.7950	0.7958	0.7972	0.7977	0.7968	0.7970
1.62	0.7127	0.7040	0.7115	0.7101	0.7045	0.7092	0.7086	0.7039	0.7062	0.7140	0.7183	0.7253	0.7337	0.7497	0.7555	0.7615	0.7754	0.7809	0.7895	0.7913	0.7958	0.7961	0.7953	0.7952
1.30	0.6097	0.6166	0.6097	0.6138	0.6055	0.6237	0.6146	0.6345	0.6267	0.6436	0.6527	0.6614	0.6854	0.7006	0.7162	0.7322	0.7526	0.7692	0.7812	0.7874	0.7930	0.7925	0.7917	0.7921
1.01	0.5052	0.5024	0.5071	0.5055	0.5126	0.5064	0.5218	0.5310	0.5573	0.5743	0.5996	0.6151	0.6418	0.6680	0.6911	0.7166	0.7427	0.7603	0.7730	0.7844	0.7891	0.7912	0.7902	0.7898
0.76	0.4050	0.4179	0.4161	0.4078	0.4130	0.4397	0.4653	0.4780	0.5062	0.5369	0.5583	0.5941	0.6191	0.6506	0.6790	0.7054	0.7311	0.7566	0.7704	0.7792	0.7867	0.7874	0.7867	0.7867
0.54	0.3244	0.3319	0.3414	0.3232	0.3570	0.3796	0.4192	0.4419	0.4697	0.5038	0.5380	0.5718	0.6015	0.6442	0.6649	0.6982	0.7248	0.7471	0.7634	0.7771	0.7829	0.7837	0.7818	0.7815
0.36	0.2465	0.2639	0.2783	0.2940	0.3215	0.3555	0.3781	0.4181	0.4469	0.4841	0.5207	0.5547	0.5910	0.6277	0.6591	0.6891	0.7136	0.7397	0.7580	0.7699	0.7783	0.7774	0.7772	0.7771
0.22	0.1997	0.2101	0.2366	0.2667	0.2938	0.3299	0.3571	0.3970	0.4341	0.4675	0.5009	0.5394	0.5784	0.6125	0.6492	0.6783	0.7058	0.7336	0.7499	0.7657	0.7713	0.7726	0.7722	0.7725
0.11	0.1589	0.1932	0.2122	0.2377	0.2735	0.3148	0.3483	0.3819	0.4159	0.4624	0.4988	0.5302	0.5725	0.6052	0.6417	0.6744	0.7008	0.7270	0.7463	0.7599	0.7662	0.7676	0.7668	0.7671
0.04	0.1319	0.1672	0.2036	0.2318	0.2640	0.3031	0.3337	0.3740	0.4166	0.4458	0.4883	0.5272	0.5632	0.5998	0.6343	0.6666	0.6975	0.7198	0.7419	0.7544	0.7615	0.7625	0.7615	0.7620

Step 1 ⟵

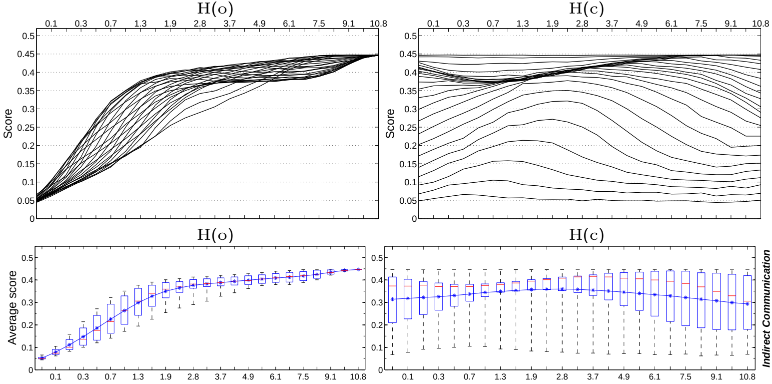
Observation entropies : **H**(o)

Communication entropies : **H**(c)	0.04	0.11	0.22	0.36	0.54	0.76	1.01	1.30	1.62	1.99	2.38	2.82	3.29	3.79	4.33	4.91	5.53	6.18	6.86	7.58	8.34	9.14	9.97	10.84
10.84	0.0506	0.0693	0.0927	0.1120	0.1329	0.1517	0.1735	0.1998	0.2256	0.2545	0.2753	0.2903	0.3059	0.3277	0.3431	0.3615	0.3833	0.4076	0.4234	0.4328	0.4439	0.4470	0.4472	0.4470
9.97	0.0469	0.0646	0.0837	0.1078	0.1290	0.1502	0.1712	0.1978	0.2256	0.2667	0.2990	0.3179	0.3297	0.3422	0.3609	0.3778	0.3933	0.4140	0.4291	0.4385	0.4448	0.4475	0.4468	0.4473
9.14	0.0450	0.0657	0.0883	0.1008	0.1203	0.1434	0.1738	0.1950	0.2486	0.2907	0.3245	0.3419	0.3491	0.3652	0.3823	0.3930	0.4073	0.4213	0.4335	0.4398	0.4470	0.4472	0.4469	0.4465
8.34	0.0441	0.0618	0.0824	0.1022	0.1200	0.1409	0.1766	0.2188	0.2637	0.3064	0.3394	0.3588	0.3695	0.3779	0.3955	0.4059	0.4180	0.4273	0.4339	0.4458	0.4470	0.4459	0.4464	0.4468
7.58	0.0461	0.0702	0.0849	0.1046	0.1222	0.1497	0.1841	0.2333	0.2793	0.3249	0.3541	0.3707	0.3845	0.3945	0.4046	0.4131	0.4231	0.4311	0.4419	0.4450	0.4449	0.4466	0.4461	0.4471
6.86	0.0489	0.0677	0.0863	0.1056	0.1274	0.1584	0.2024	0.2542	0.3105	0.3445	0.3696	0.3828	0.3943	0.4005	0.4111	0.4202	0.4268	0.4389	0.4410	0.4448	0.4458	0.4465	0.4463	0.4467
6.18	0.0486	0.0671	0.0875	0.1076	0.1313	0.1676	0.2249	0.2817	0.3274	0.3575	0.3752	0.3897	0.4002	0.4079	0.4153	0.4229	0.4325	0.4383	0.4388	0.4409	0.4432	0.4438	0.4451	0.4468
5.53	0.0478	0.0720	0.0927	0.1139	0.1470	0.1853	0.2503	0.3062	0.3457	0.3669	0.3827	0.3969	0.4053	0.4119	0.4172	0.4284	0.4327	0.4318	0.4360	0.4362	0.4386	0.4404	0.4438	0.4467
4.91	0.0506	0.0721	0.0959	0.1199	0.1556	0.2088	0.2733	0.3255	0.3614	0.3770	0.3872	0.4016	0.4080	0.4141	0.4236	0.4295	0.4293	0.4306	0.4336	0.4353	0.4370	0.4408	0.4442	0.4468
4.33	0.0506	0.0701	0.0965	0.1268	0.1726	0.2388	0.3002	0.3446	0.3698	0.3875	0.3941	0.4053	0.4136	0.4202	0.4246	0.4255	0.4271	0.4294	0.4299	0.4300	0.4330	0.4395	0.4436	0.4471
3.79	0.0498	0.0745	0.1018	0.1413	0.1971	0.2685	0.3224	0.3579	0.3803	0.3893	0.3989	0.4073	0.4157	0.4187	0.4167	0.4197	0.4231	0.4227	0.4220	0.4249	0.4294	0.4373	0.4432	0.4469
3.29	0.0528	0.0741	0.1050	0.1534	0.2286	0.2955	0.3363	0.3670	0.3859	0.3960	0.4037	0.4103	0.4165	0.4138	0.4168	0.4179	0.4162	0.4171	0.4158	0.4182	0.4256	0.4344	0.4425	0.4470
2.82	0.0486	0.0790	0.1126	0.1686	0.2504	0.3151	0.3456	0.3732	0.3870	0.3982	0.4038	0.4132	0.4081	0.4109	0.4119	0.4135	0.4108	0.4071	0.4122	0.4128	0.4186	0.4308	0.4414	0.4464
2.38	0.0533	0.0809	0.1203	0.1881	0.2643	0.3216	0.3506	0.3770	0.3906	0.4011	0.4066	0.4046	0.4056	0.4054	0.4018	0.3999	0.4014	0.3987	0.4034	0.4102	0.4165	0.4279	0.4403	0.4463
1.99	0.0530	0.0836	0.1338	0.2069	0.2717	0.3202	0.3493	0.3731	0.3897	0.3976	0.3947	0.4017	0.4001	0.3958	0.3948	0.3917	0.3913	0.3956	0.3948	0.4023	0.4113	0.4285	0.4404	0.4465
1.62	0.0533	0.0898	0.1457	0.2127	0.2681	0.3125	0.3444	0.3705	0.3893	0.3902	0.3907	0.3919	0.3939	0.3867	0.3846	0.3856	0.3862	0.3843	0.3869	0.3990	0.4083	0.4269	0.4404	0.4461
1.30	0.0570	0.0929	0.1562	0.2140	0.2566	0.2991	0.3378	0.3690	0.3729	0.3830	0.3816	0.3879	0.3829	0.3784	0.3774	0.3800	0.3791	0.3811	0.3873	0.3899	0.4062	0.4238	0.4391	0.4469
1.01	0.0565	0.1033	0.1582	0.2100	0.2538	0.2894	0.3195	0.3447	0.3622	0.3741	0.3772	0.3811	0.3755	0.3741	0.3739	0.3752	0.3779	0.3805	0.3830	0.3926	0.4056	0.4247	0.4397	0.4468
0.76	0.0604	0.1051	0.1568	0.1969	0.2339	0.2635	0.2985	0.3269	0.3488	0.3615	0.3665	0.3693	0.3705	0.3718	0.3727	0.3745	0.3757	0.3811	0.3799	0.3886	0.4017	0.4243	0.4403	0.4467
0.54	0.0645	0.1002	0.1448	0.1849	0.2159	0.2478	0.2758	0.3061	0.3352	0.3500	0.3577	0.3635	0.3705	0.3736	0.3757	0.3771	0.3747	0.3794	0.3813	0.3890	0.4008	0.4220	0.4392	0.4468
0.36	0.0660	0.0956	0.1355	0.1637	0.1899	0.2197	0.2580	0.2882	0.3188	0.3381	0.3560	0.3650	0.3705	0.3741	0.3781	0.3798	0.3828	0.3873	0.3853	0.3899	0.4022	0.4216	0.4405	0.4467
0.22	0.0605	0.0917	0.1150	0.1514	0.1777	0.2061	0.2378	0.2714	0.3023	0.3317	0.3498	0.3643	0.3768	0.3797	0.3817	0.3877	0.3910	0.3916	0.3941	0.3958	0.4058	0.4231	0.4420	0.4472
0.11	0.0548	0.0779	0.0997	0.1313	0.1592	0.1893	0.2186	0.2520	0.2864	0.3165	0.3372	0.3630	0.3728	0.3845	0.3911	0.3952	0.4016	0.4032	0.4024	0.4090	0.4137	0.4274	0.4422	0.4469
0.04	0.0486	0.0676	0.0919	0.1146	0.1400	0.1715	0.2025	0.2317	0.2671	0.2987	0.3307	0.3542	0.3734	0.3890	0.3970	0.4031	0.4091	0.4116	0.4141	0.4194	0.4265	0.4305	0.4422	0.4464

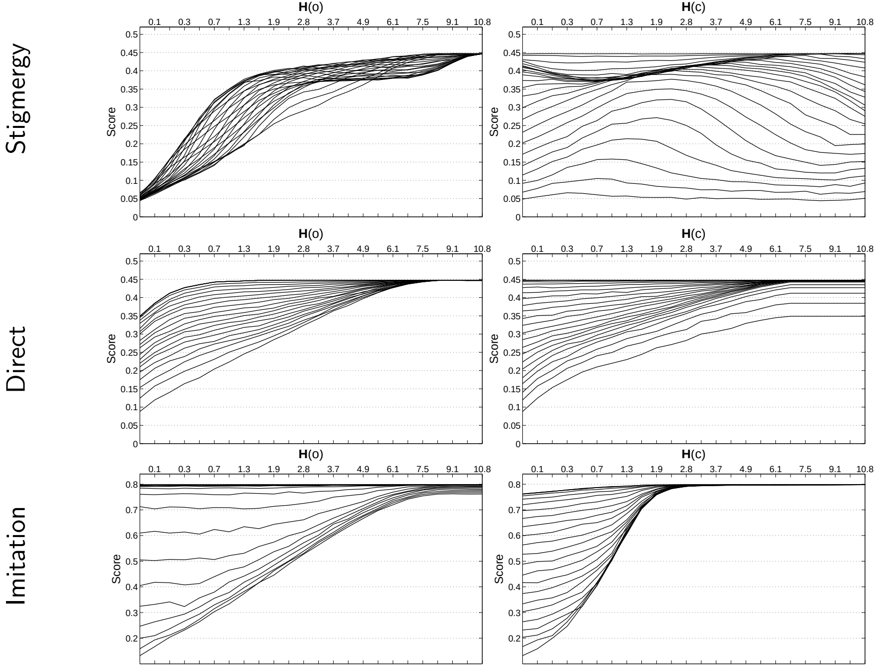
Indirect communication

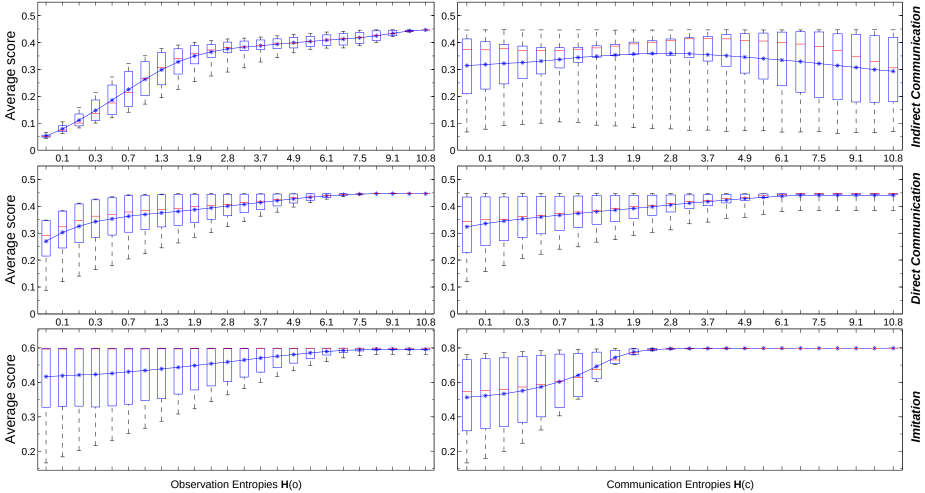
Step 2 ⟵

Step 3



Communication mode





Whisker plot showing the variation in test scores across different entropy values $\mathrm{H}(c)$ for fixed entropies $\mathrm{H}(o)$ (left-side), and vice versa (right-side). The central mark (in red) is the median while the edges of the box represent the 25^{th} and 75^{th} percentiles of the scores and the whiskers extend to the most extreme score values. The blue line-plot shows the average scores at each of the intermediate entropy values.

Coefficient of success ϕ

Definition

Communication-over-observation coefficient of success is:

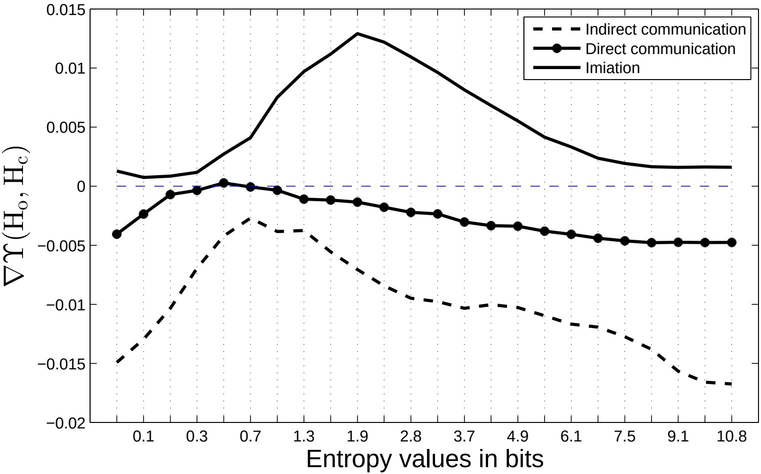
$$\phi = \frac{success(communication > observation)}{number\ \ of\ \ tests}$$

- ϕ close to 1 $\implies$ communication has higher influence on intelligence
- ϕ close to 0 $\implies$ observation has higher influence on intelligence

Coefficient of success ϕ

Communication mode	ϕ	*Dependency*
stigmergy	0.0399	high
direct communication	0.9855	low
imitation	0.9928	low

Entropy analysis



Presentation Outline

Scope of experiments

- Different Environment spaces
  - different uncertainties
- Number of evaluated agents
- Heterogeneous collectives
- Different communication methods
- Measure *learning* rather than *search*
  - how does the collective performance vary with the task/problem complexity ?

What is the bottom line re communication and observation?

- Dull systems with low perception abilities can be re-compensated for and significantly improved by introducing a measurable amount of communication
- Increasing the communication entropies does not imply a monotonic increase in intelligence
- Communication can be highly dependent on observation and this dependency can be measured
- There exists a restricted range of entropies where communication achieves its highest influence on the group's intelligence

Possible applications:

- searching for a moving target while avoiding injury (collective pursuit problems)
- nest selection when there is one and only one best nest
- pattern recognition problems

Thank you

Questions?

References

Motivation
Methodology
Experiments
Results
Conclusions and future work
Q/A
References

Chmait, N., Dowe, D.L., Green, D.G., Li, Y.F., Insa-Cabrera, J.: Measuring universal intelligence in agent-based systems using the anytime intelligence test. Tech. Rep. 2015/279, Faculty of Information Technology, Clayton, Monash University (2015), http://www.csse.monash.edu.au/publications/2015/tr-2015-279-full.pdf

Hernández-Orallo, J., Dowe, D.L.: Measuring universal intelligence: Towards an anytime intelligence test. Artif. Intell. 174(18), 1508–1539 (Dec 2010), http://dx.doi.org/10.1016/j.artint.2010.09.006

Insa-Cabrera, J., Benacloch-Ayuso, J.L., Hernández-Orallo, J.: On measuring social intelligence: Experiments on competition and cooperation. In: Bach, J., Goertzel, B., Ikl, M. (eds.) Artificial General Intelligence, Lecture Notes in Computer Science, vol. 7716, pp. 126–135. Springer Berlin Heidelberg (2012), http://dx.doi.org/10.1007/978-3-642-35506-6_14

Legg, S., Hutter, M.: Universal intelligence: A definition of machine intelligence. Minds and Machines 17(4), 391–444 (Dec 2007)

Panait, L., Luke, S.: Cooperative multi-agent learning: The state of the art. Autonomous Agents and Multi-Agent Systems 11(3), 387–434 (Nov 2005), http://dx.doi.org/10.1007/s10458-005-2631-2

Shannon, C.: A mathematical theory of communication. Bell System Technical Journal, The 27(3), 379–423 (July 1948)

Coefficient of success

Definition

Let $S = \{(x, y) \in E \times E \mid x > y\}$. The communication-over-observation coefficient of success is: $\phi = (\sum_S \inf(\Upsilon(x, y), \Upsilon(y, x)) \div |S|)$, where $\inf(a, b)$ is a function that returns 1 if $a < b$, or zero otherwise.

Knowing that the test scores are of the form $\Upsilon(\mathrm{H_o}, \mathrm{H_c})$:

- ϕ close to 1 $\implies$ communication has higher influence on intelligence
- ϕ close to 0 $\implies$ observation has higher influence on intelligence