Evolving ROP Chains

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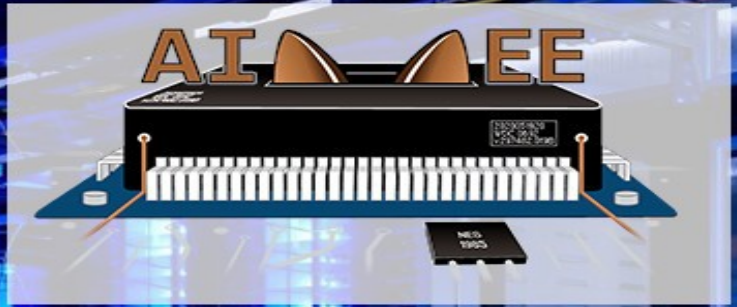
Special Circumstances LLC

History of Return Oriented Programming

History of ROP

- At the beginning stacks were executable
- Buffer overflow attacks were simple:
  1) Overwrite return address to point to stack
  2) Follow return address with code to be ran
- Stack position was randomized (ASLR)
  - Increase the injected program size adding No Operation (NOP) instructions to make falling somewhere in those instructions likely
- Stack was made non executable
  - Find already executable code that could be useful (gadgets)
  - Make them return in to each other to attain desired result (ROP)



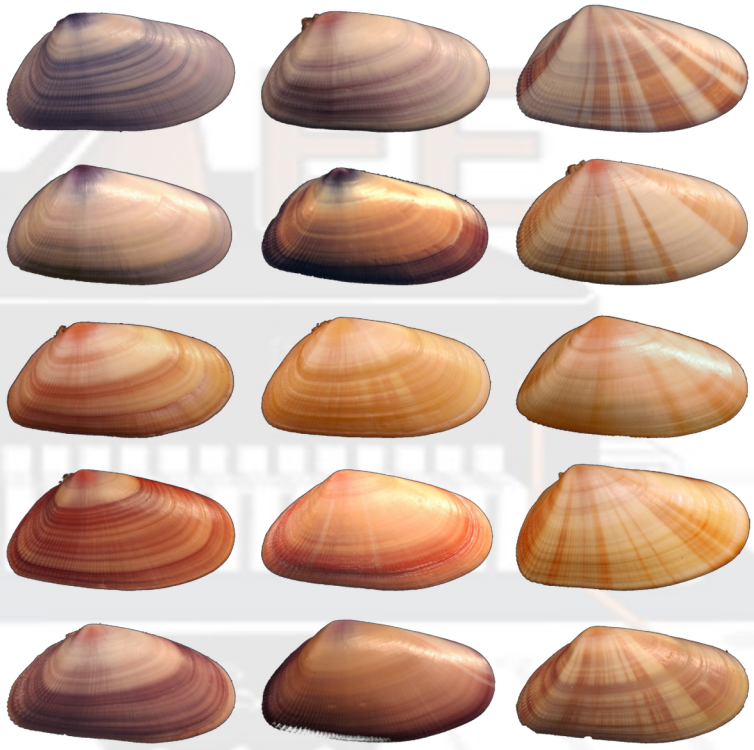
Genetic Programming Design Decisions

Genotypes: Two Approaches

1) Vector of machine words
   - Each genotype a potential ROP payload
   - Phenotype developed by
     - Writing genotype to the stack of the (emulated) target process
     - Setting the IP to the head
     - Incrementing the SP
     - Executing emulation
2) Vector of instructions intermediary, payload-constructing VM
   - Programs aware of memory image
   - Semantic analysis primitives available
   - Outputs a payload of type (1)...

Phenotype

- Execution behaviour monitored through Unicorn hooks and callbacks
- Attributes are committed to record only when the execution reaches a composable point – a return, for example.
- A variety of attributes are recorded
- A fitness formula, with these attributes for variables, is given by experiment configuration file
- Fitness scalar obtained by evaluated fitness formula



Selection

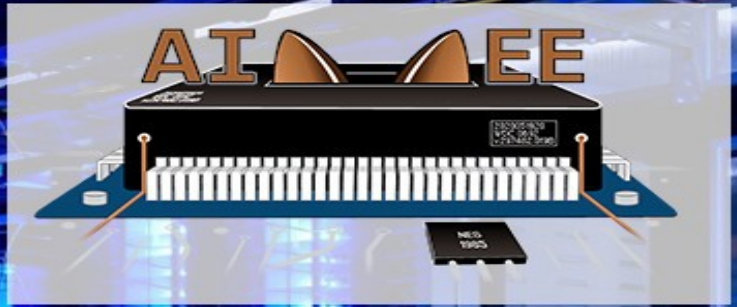
- Different methodologies tested:
  - Roulette
  - Pareto front
  - Lexicase
  - Tournament selection
- Tournament selection performed best
  - Optional geography
  - N (usually 5) contestants drawn on each iteration and evaluated
  - P (usually 2) best are bred
  - P offspring displace the P worst performers

Geography

1) Islands with migration
   - Simple parallelization
   - Fosters diversity
   - Each island is handled independently
   - Each island may send or receive individuals through a shared “pier” (lockfree queue) randomly
2) Linear geographies
   - Circular buffer on each island
   - First contestant picked randomly
   - Other contestants picked from neighbors within n slots
     - If n is the buffer size selection is unrestricted

Genetic operators

- Alternating crossover
  - Stitch together from alternating between parents
  - Length from exp. dist.
  - Prevents genetic bloat (maximum child length = maximum parent length)
- Single point crossover
  - Pick two cut points and concatenate results
- Mutation
  - Integer bitwise operators
  - Replace with memory reference
  - Replace with memory contents



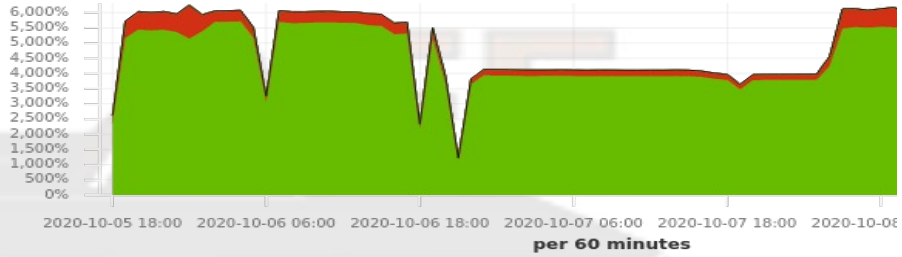
Technical obstacles

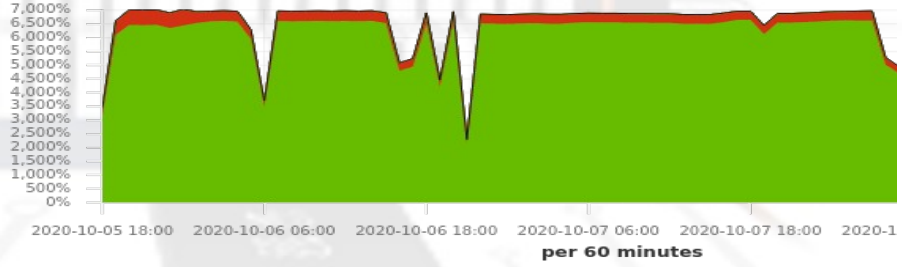
Race condition in unicorn

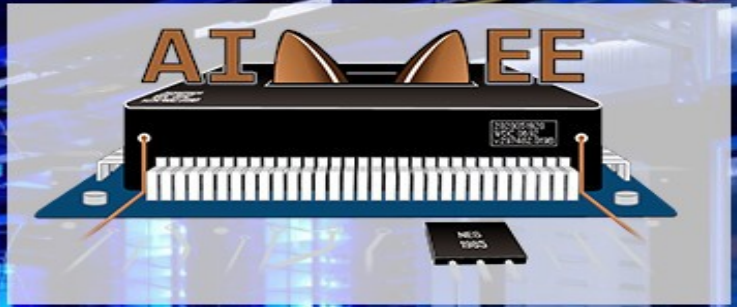
- Infrequent segmentation faults encountered in large-scale experiments
- Traces point to null struct write on unicorn library
- Cause: timeout callbacks racing against main thread
- Solution: synchronize accesses using a mutex

CPU scalability issues

- Benchmarks testing slowed down by the race condition
- Once fixed system won’t scale over 4/5 cores
- But system load shows enough workers were waiting
- Suspected causes are memory or I/O pressure







Experiments

The Effects of Phenotypic Novelty Pressures

Zero Count Experiment

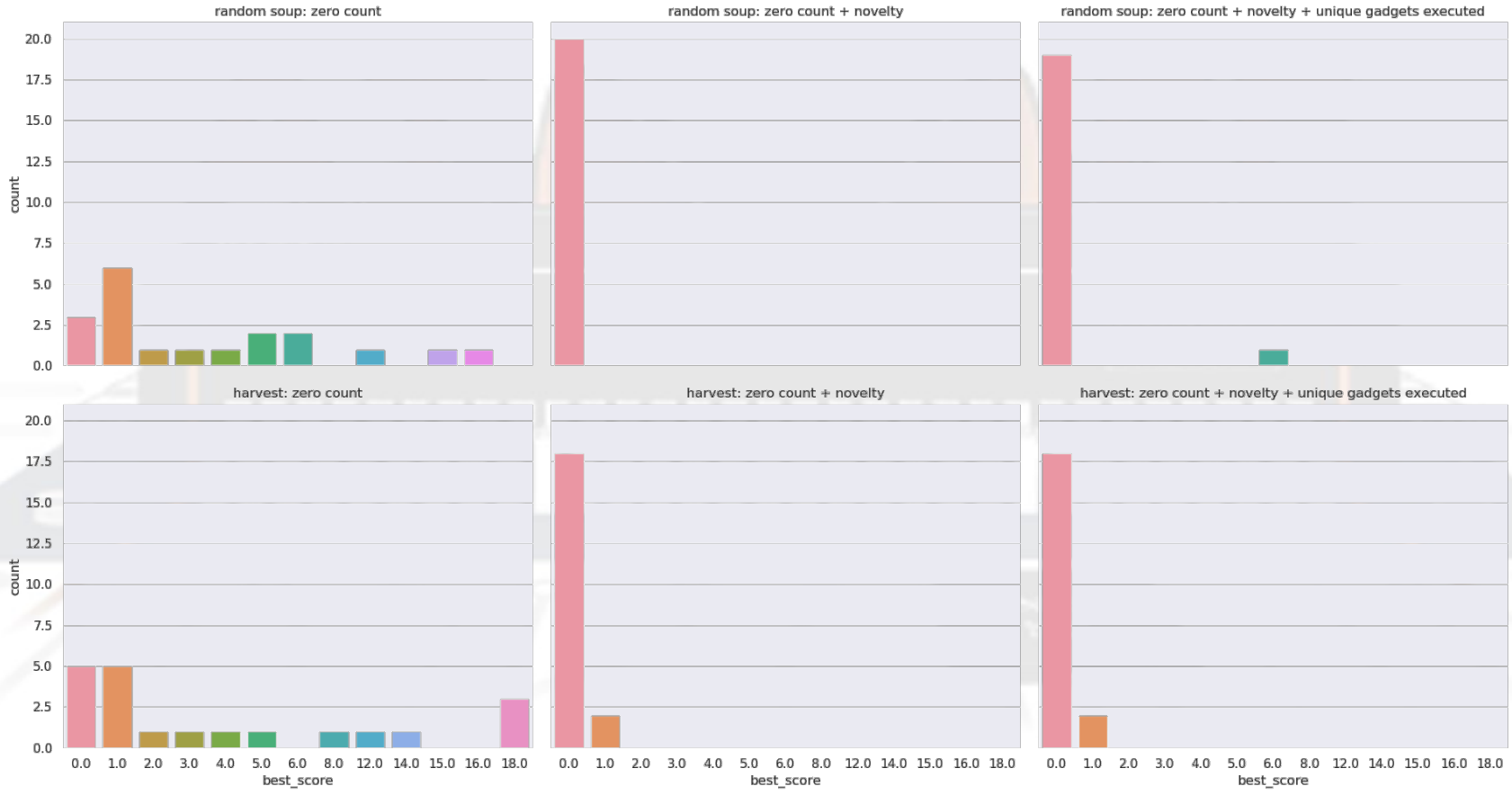
- Objective is to minimize the zero bits in the bitwise product:

  `EAX & EBX & ECX & EDX`

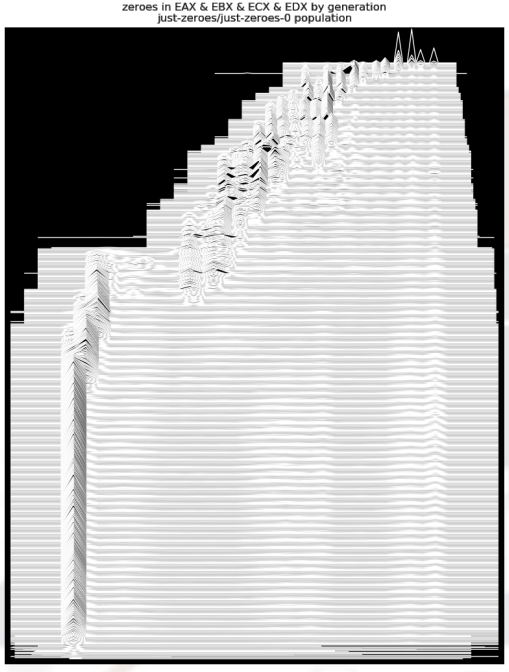
- Target binary is a statically compiled OpenSSH_6.8p1 for i386 architecture

- Phenotypic novelty is measured by feeding resulting register vectors into a CountMinSketch
- We compare runs in which novelty is a component of the fitness score, with runs in which it is not

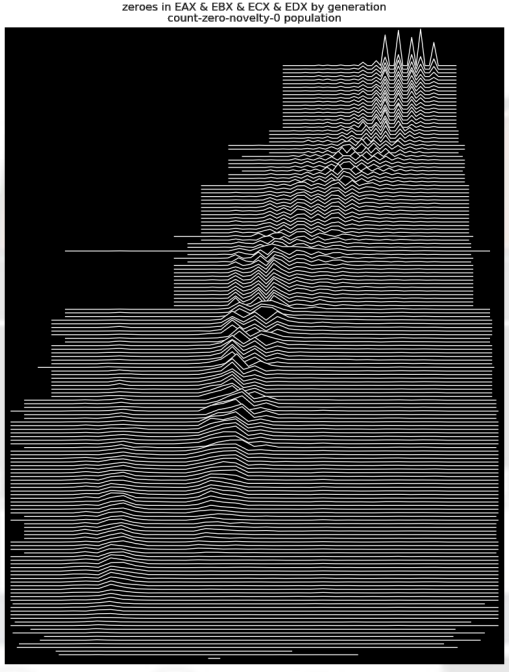
Distribution of Solutions



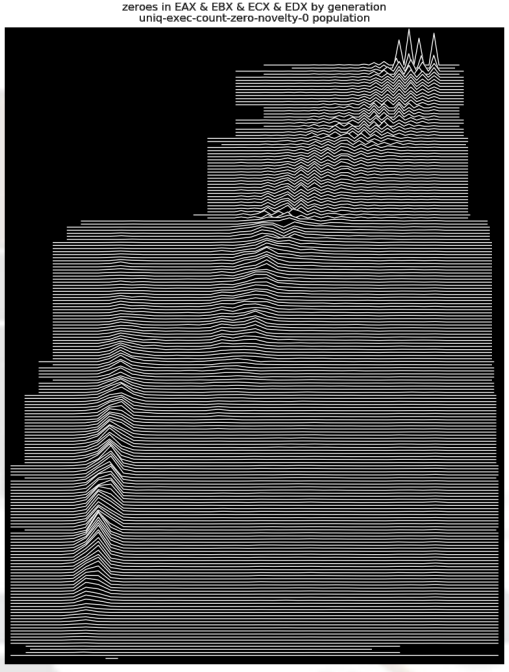
Distribution of Fitness by Generation



No novelty pressure



With novelty pressure



With novelty + unique executed gadget pressure

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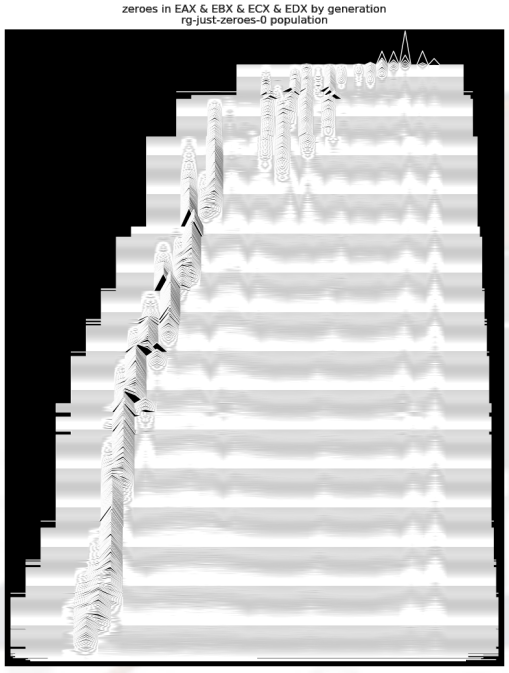
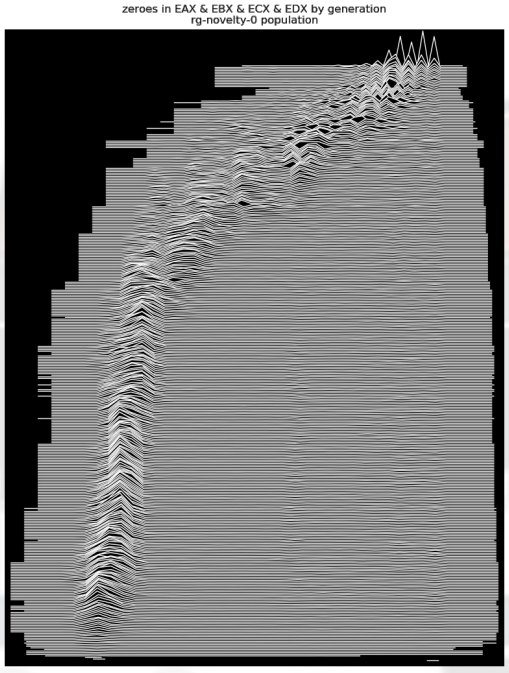
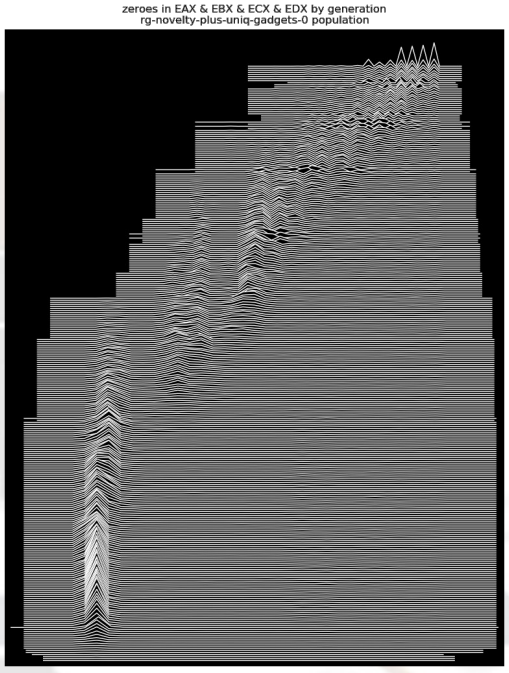


No novelty pressure



With novelty pressure



With novelty + unique executed gadget pressure

Sex & Composability

Sexual reproduction and composability

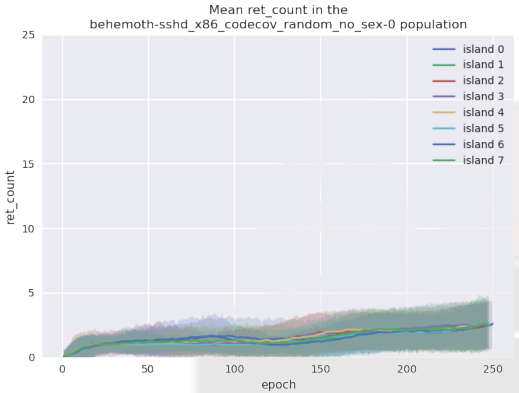
- The mixability theory for the role of sex in evolution holds that sexual reproduction favours the emergence of genes that perform well in multiple genetic contexts.
- Our conjecture: crossover should favour gadgets that **compose well** with others.

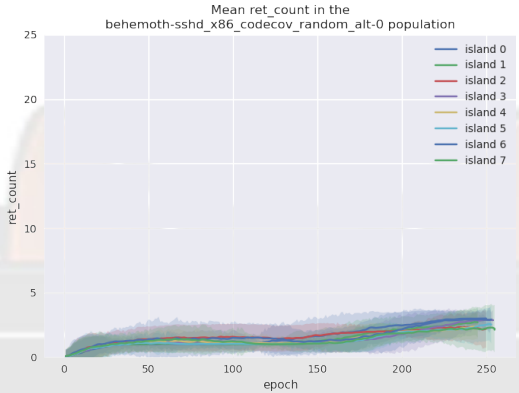
- See: Adi Livnata, Christos Papadimitrioub, Jonathan Dushoffc, & Marcus W. Feldmand, "**A mixability theory for the role of sex in evolution**", PNAS December 16, 2008 105 (50) 19803-19808.

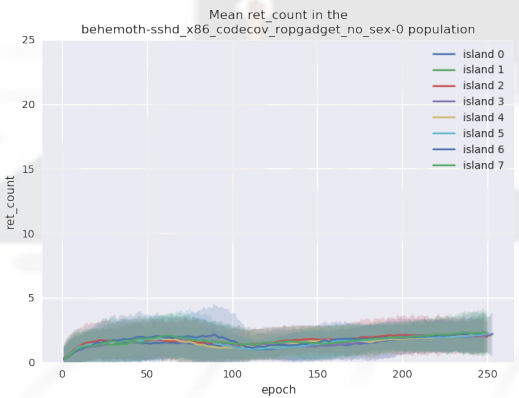
Sexual reproduction and composability

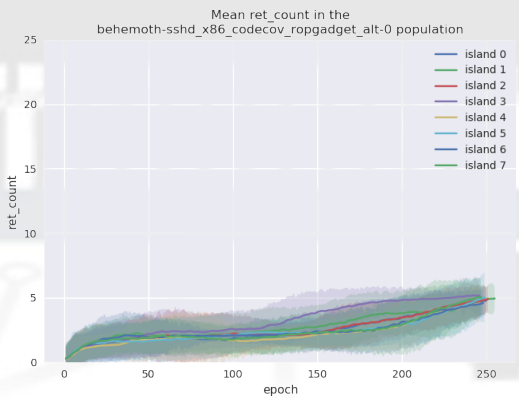
- Tested three crossover approaches:
  - Asexual (only mutations)
  - Alternating
  - Single-Point
- Tested two seeding techniques:
  - Random initial values
  - Values extracted by ROPgadget
- Metrics:
  - Return instruction executed
  - Code coverage
  - Allele circulation
  - Generational distribution
- Fitness function: code coverage

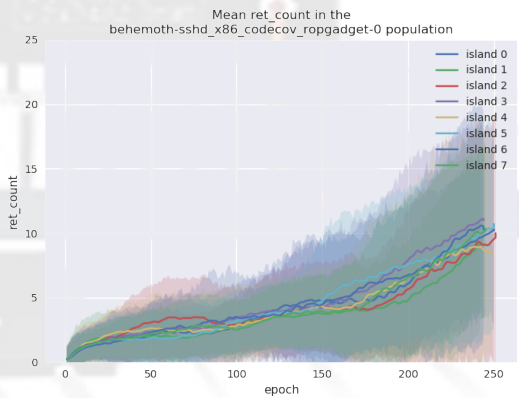
Return Count











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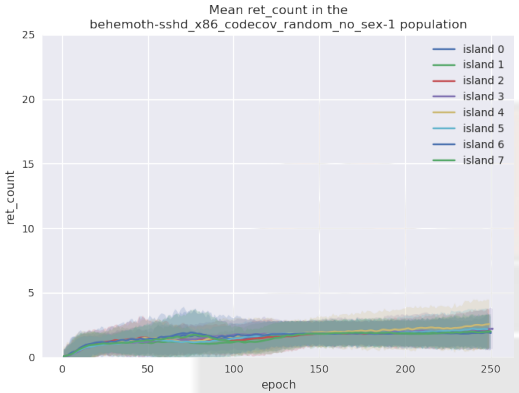

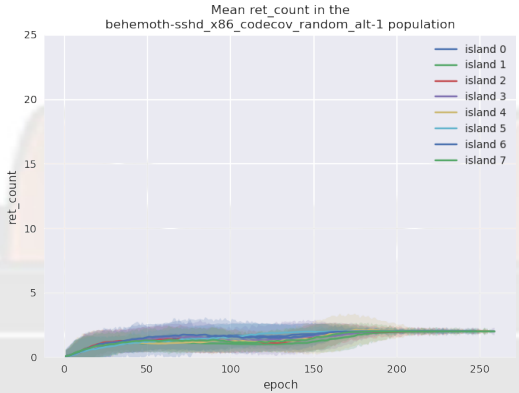

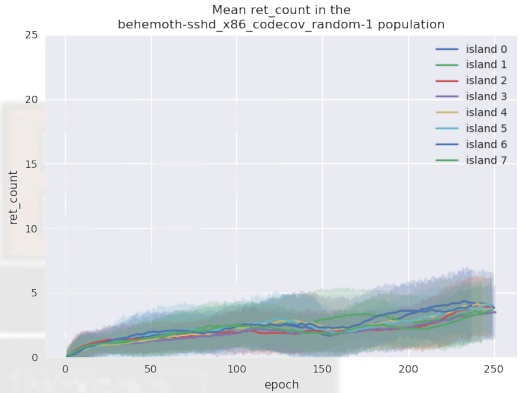

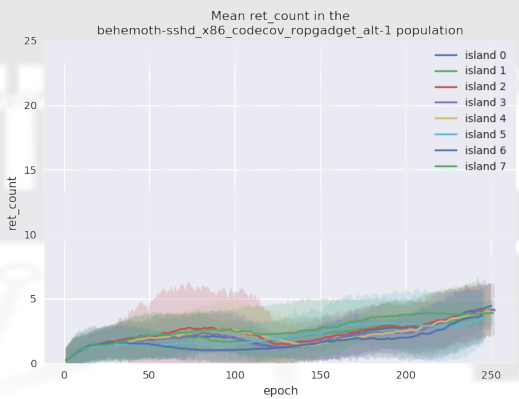

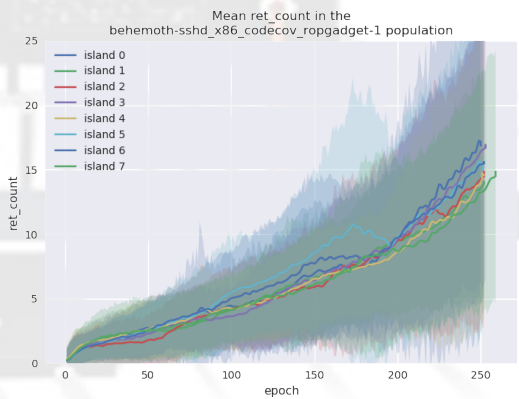

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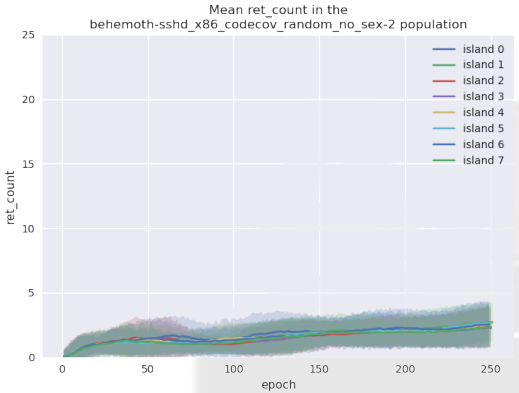
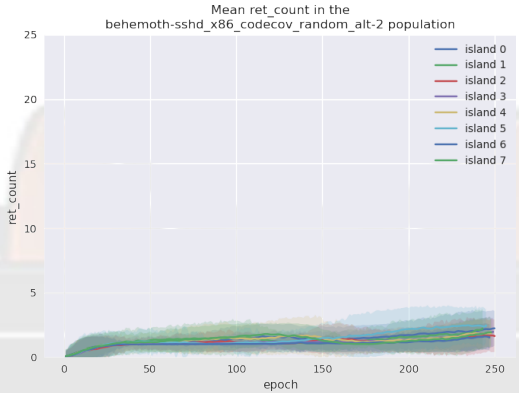
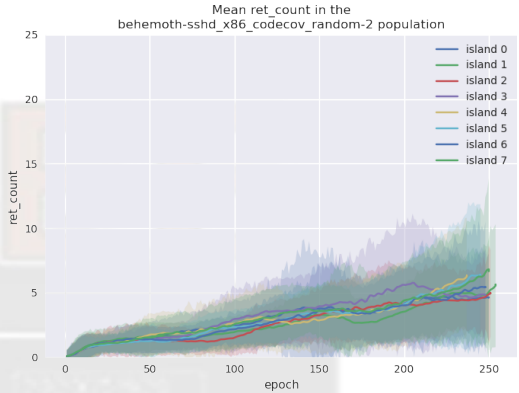
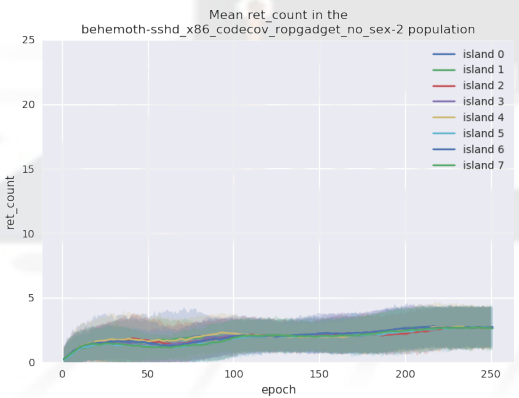
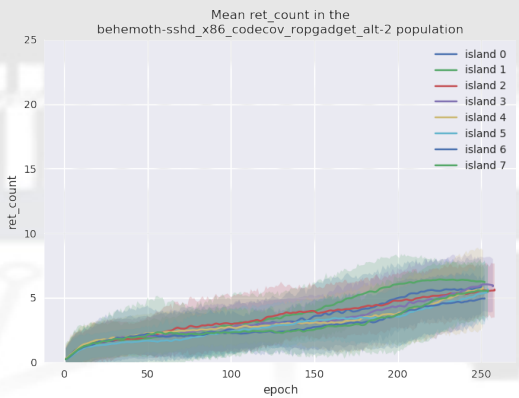


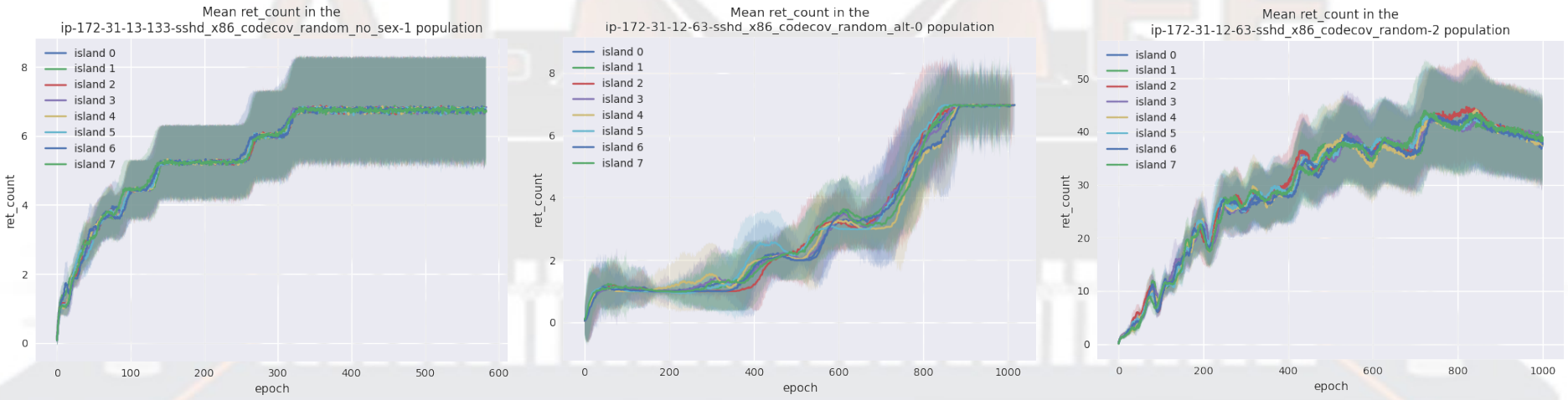




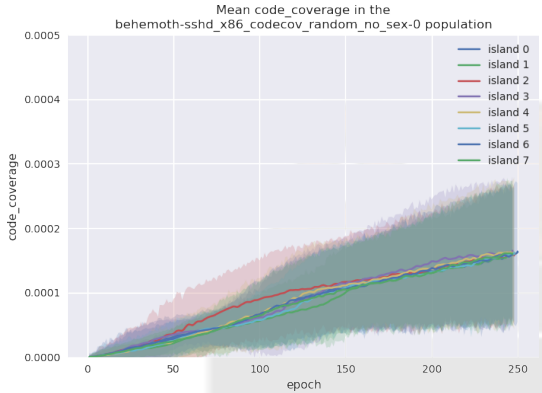


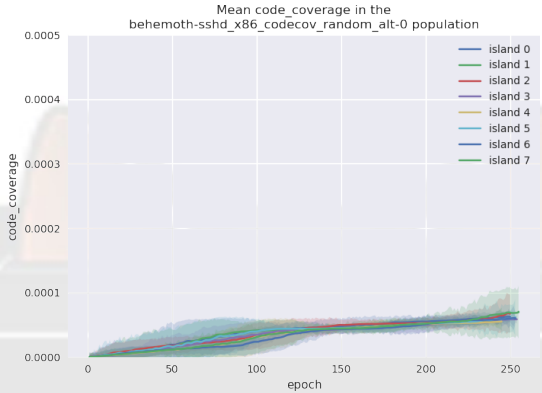


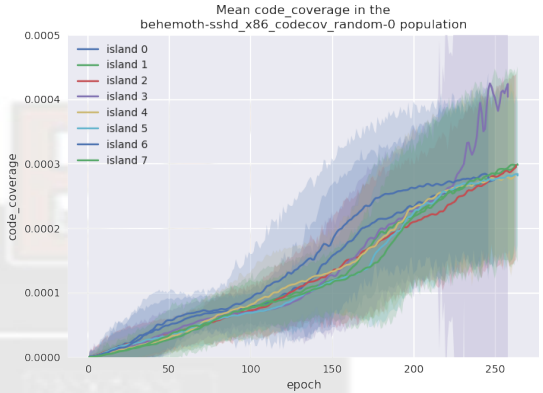
Return Count (long runs, not scaled)

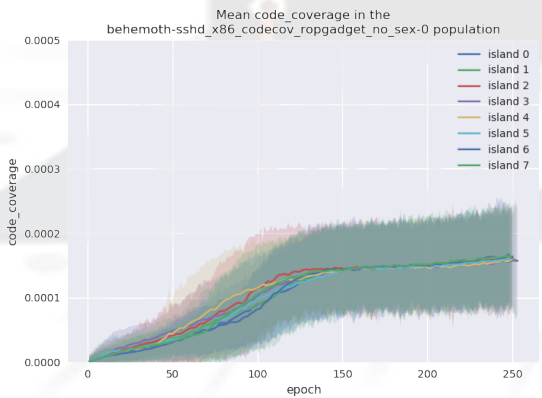


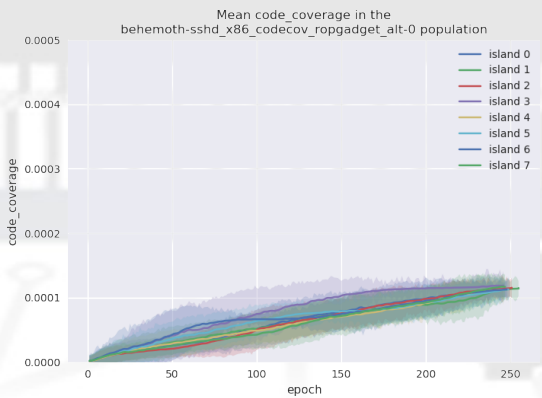
Code Coverage

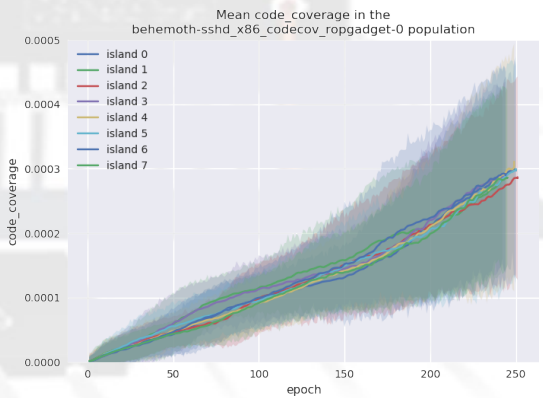












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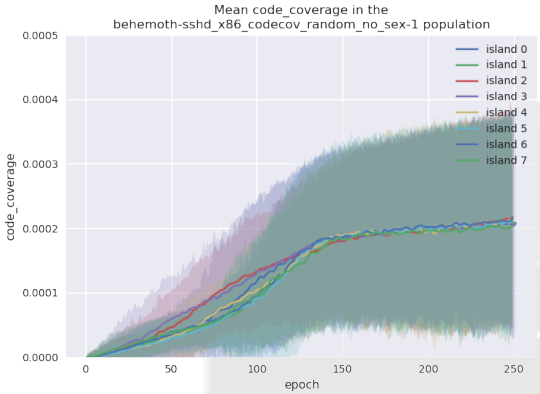

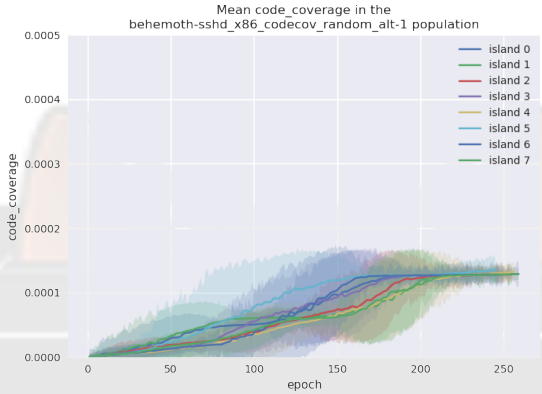

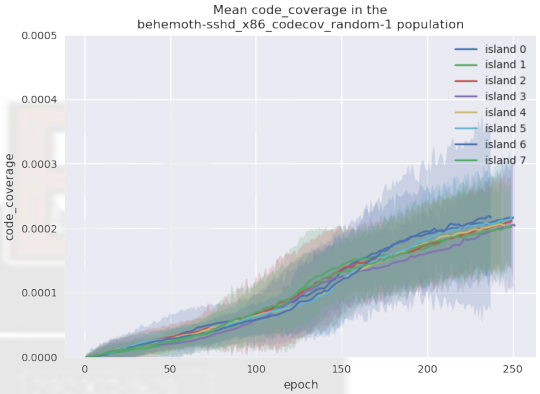

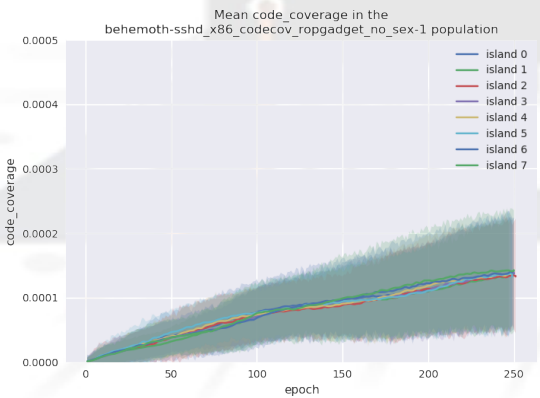

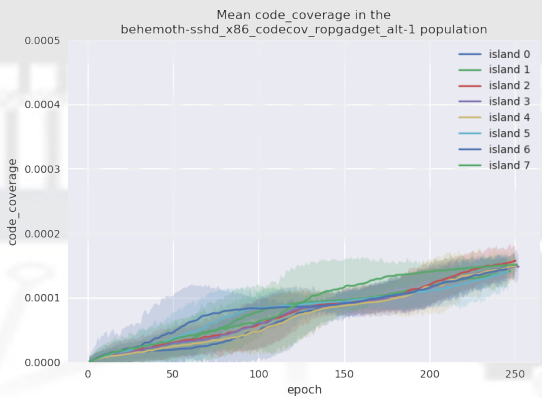

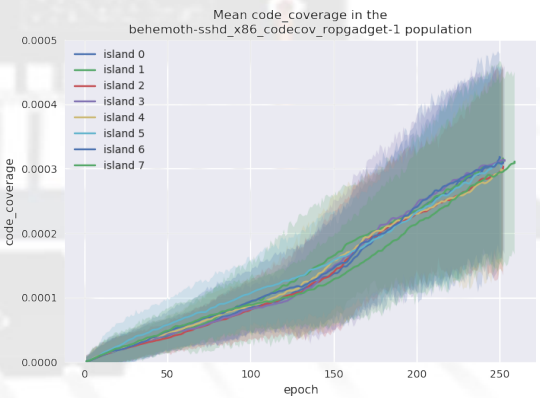

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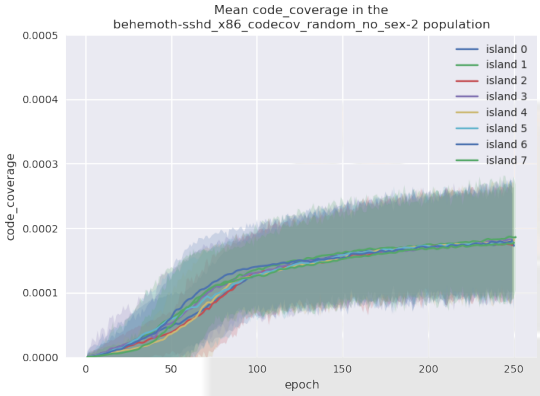
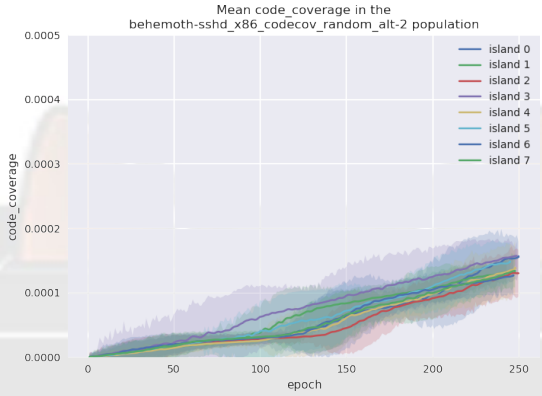
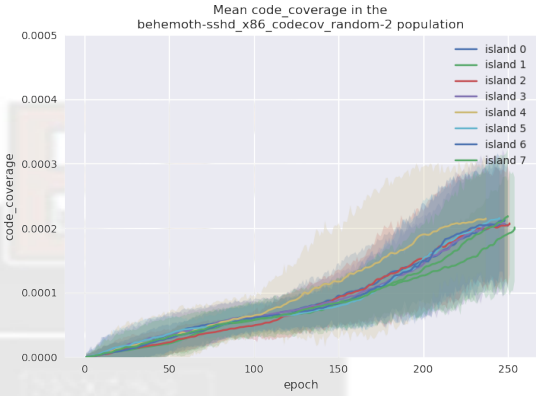
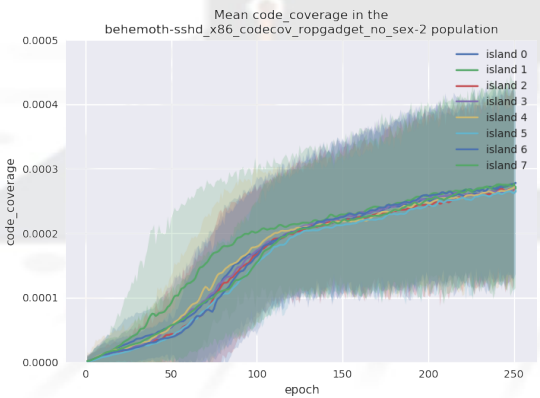
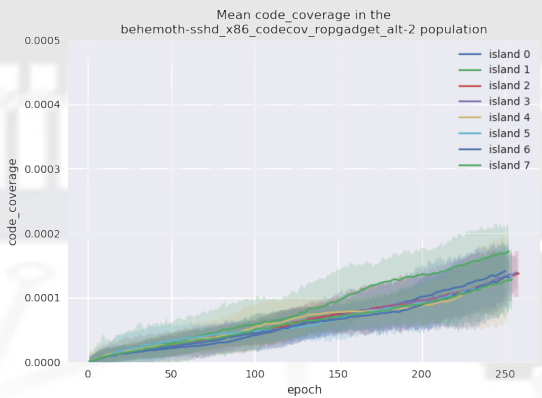
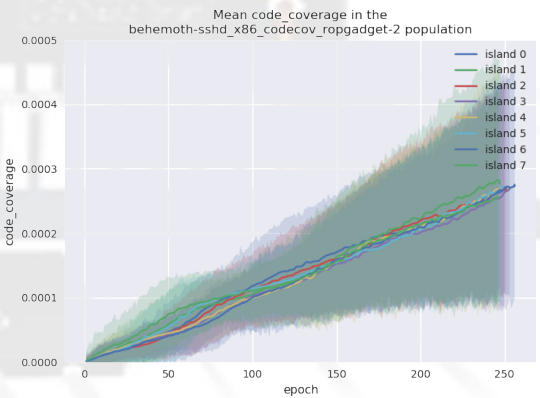




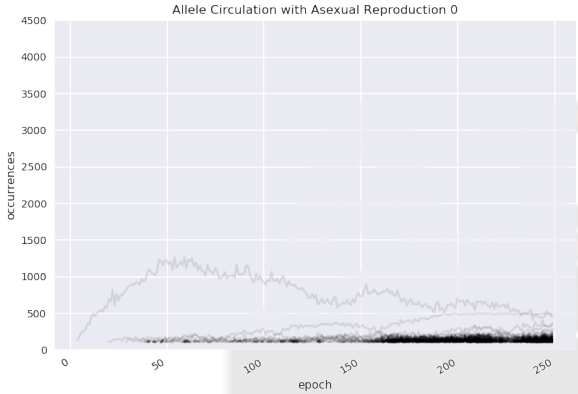


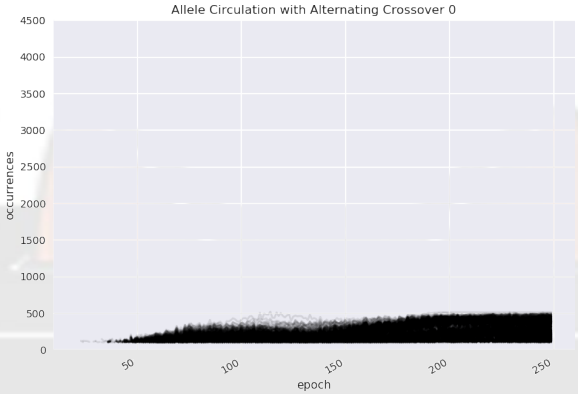


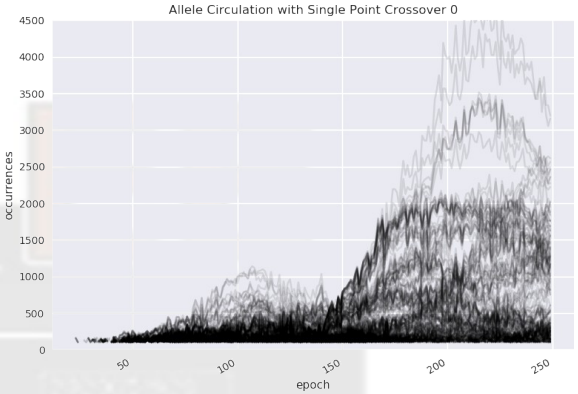


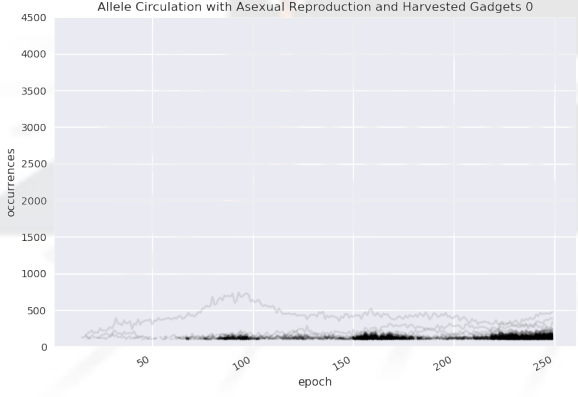


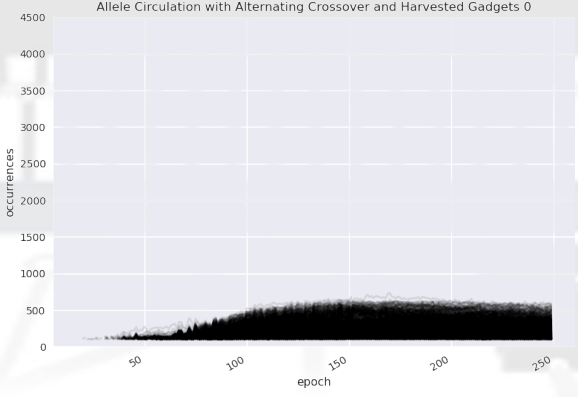
Allele Circulation

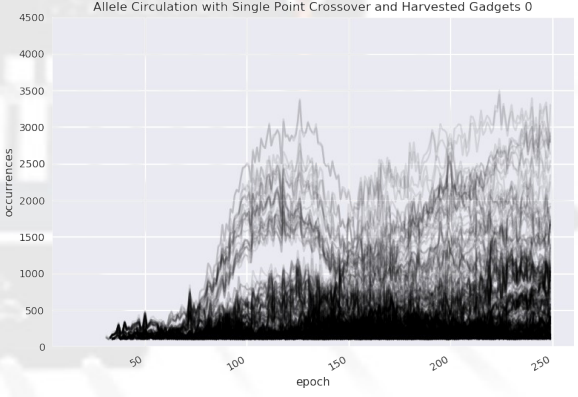












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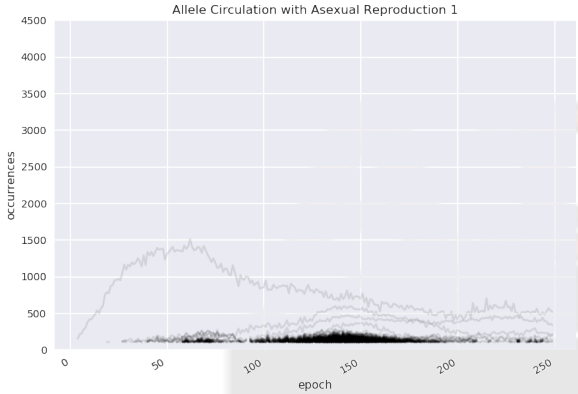
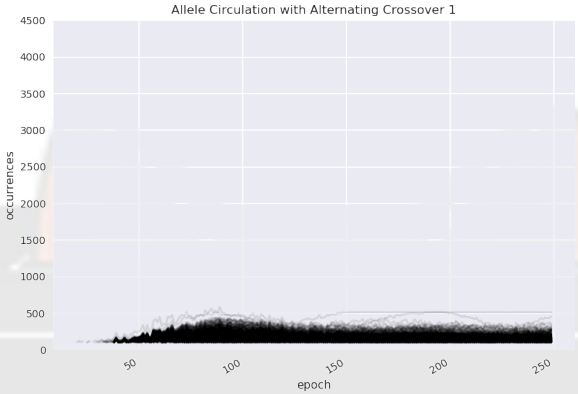
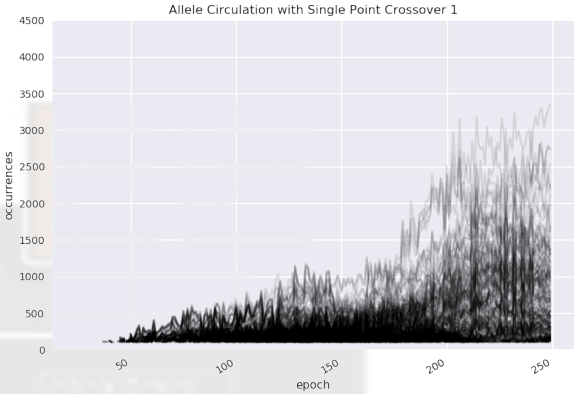
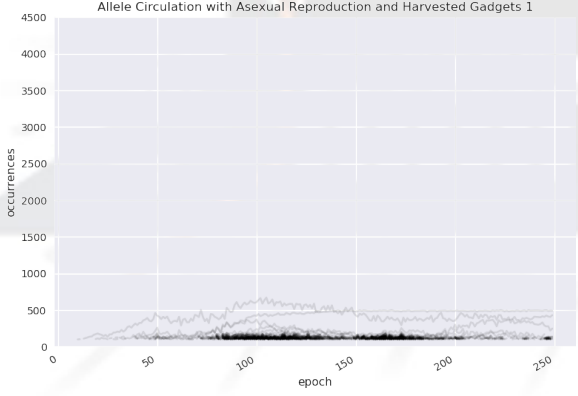
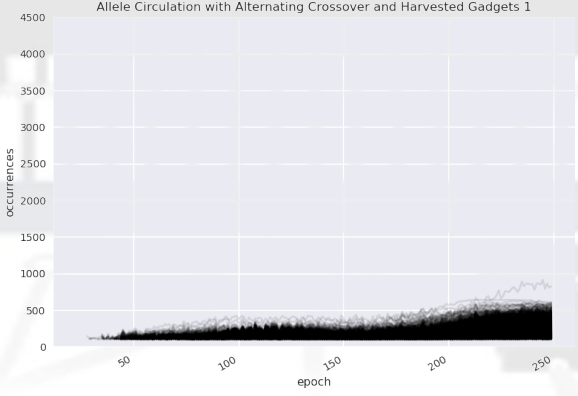
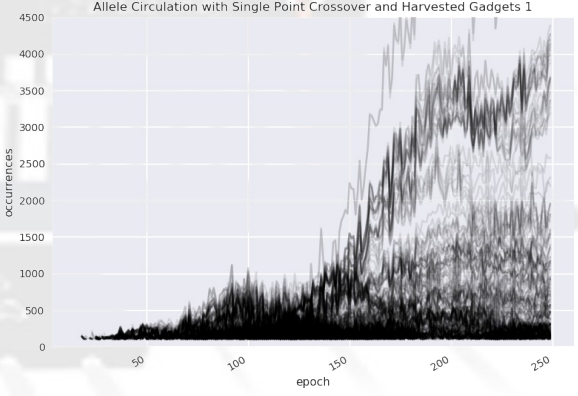




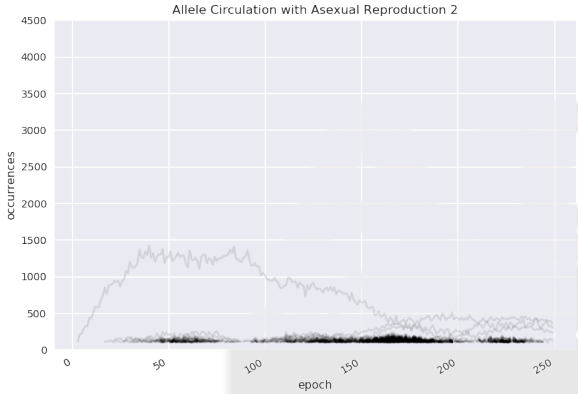


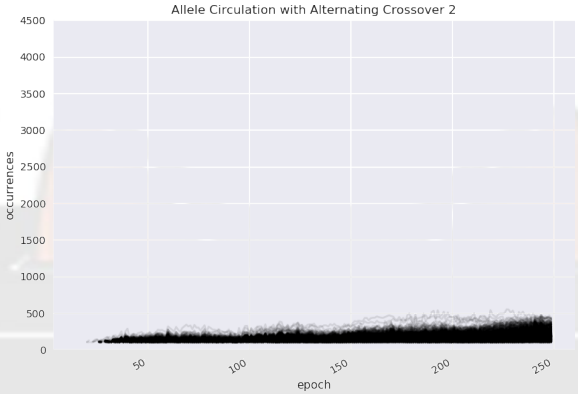


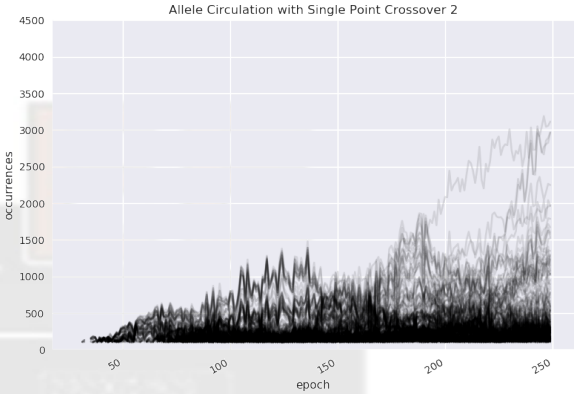


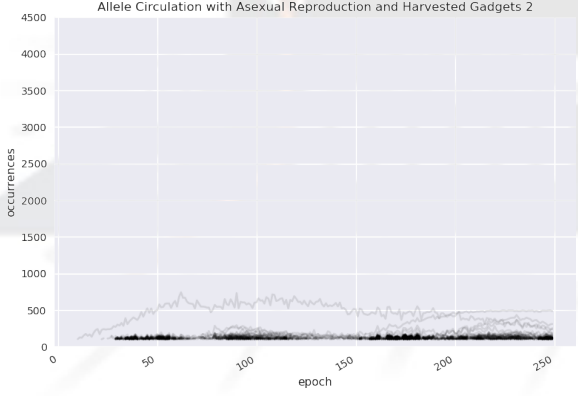


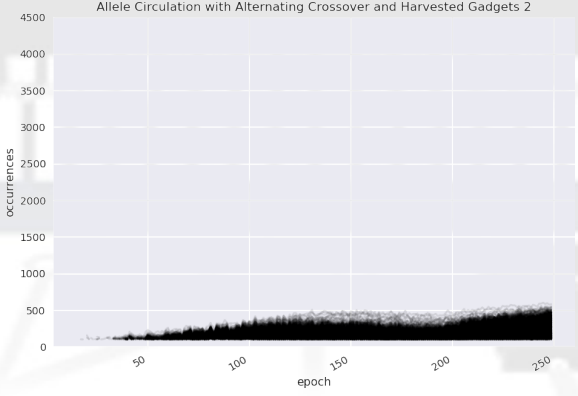
Allele Circulation

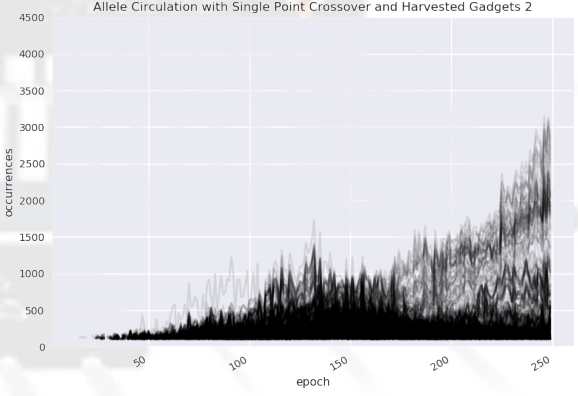


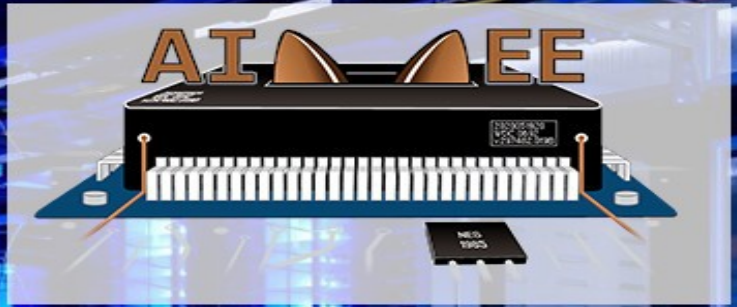






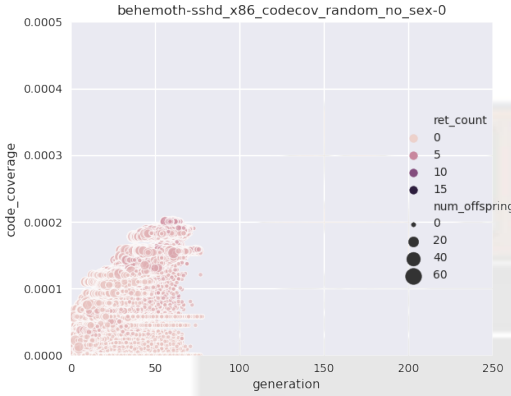


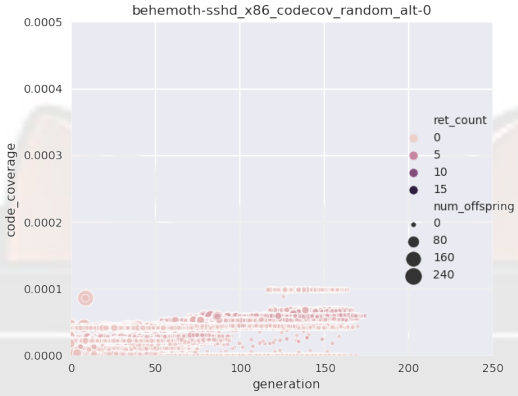


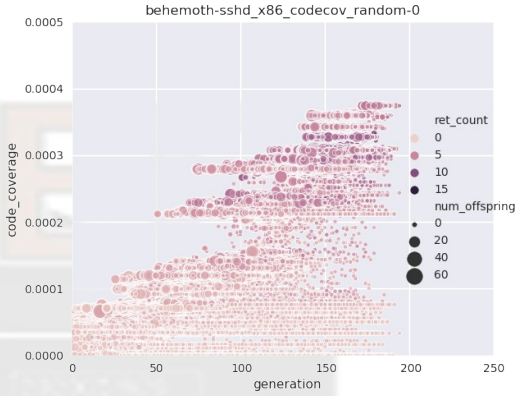


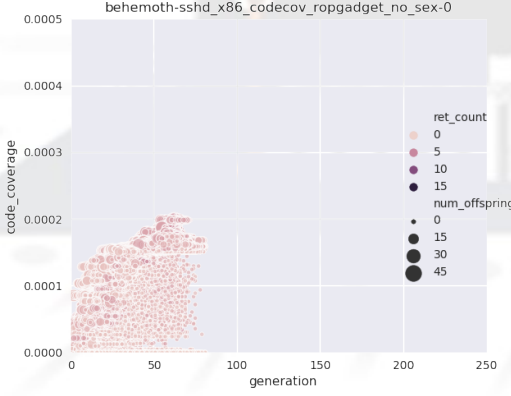
Generational distribution

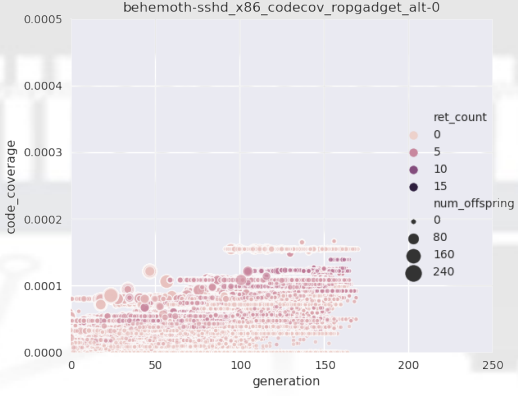
Generational Distribution

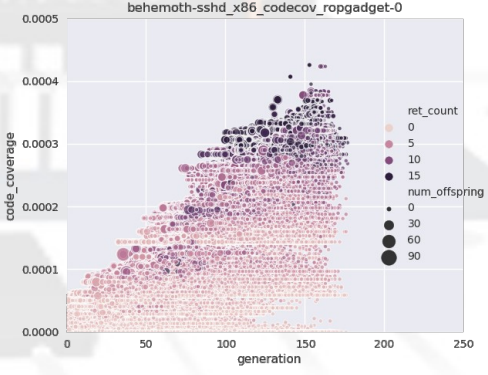




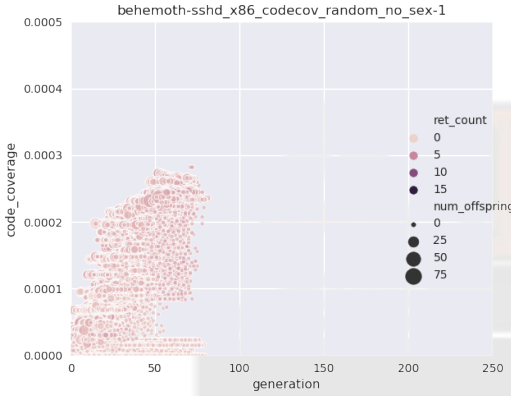


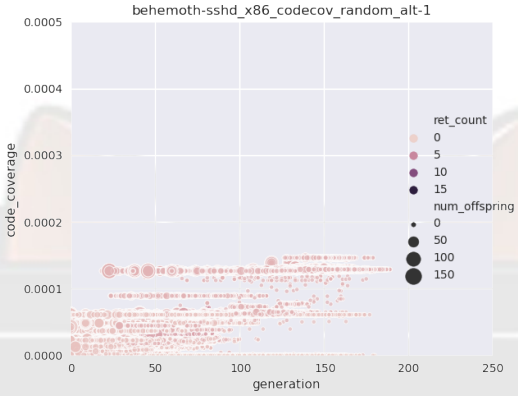


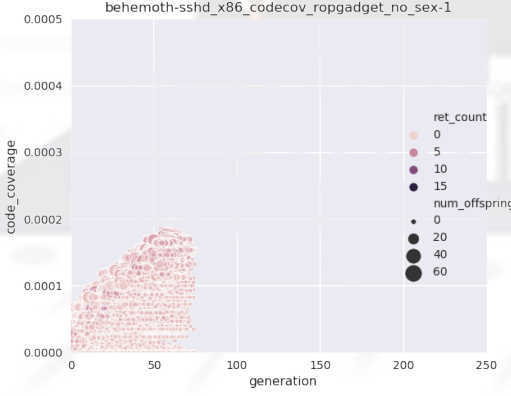


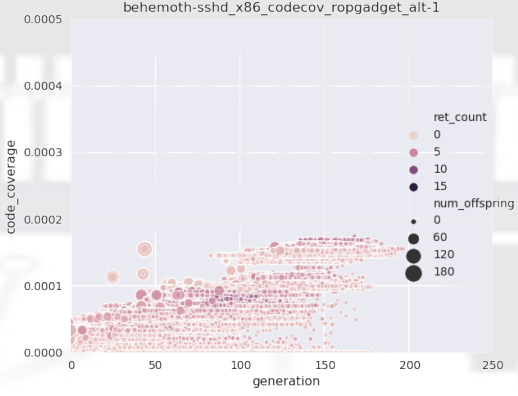


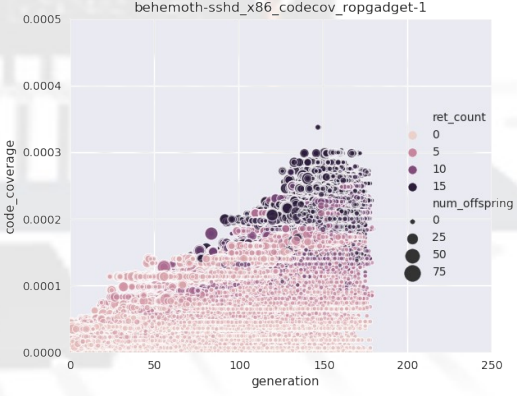
Generational Distribution











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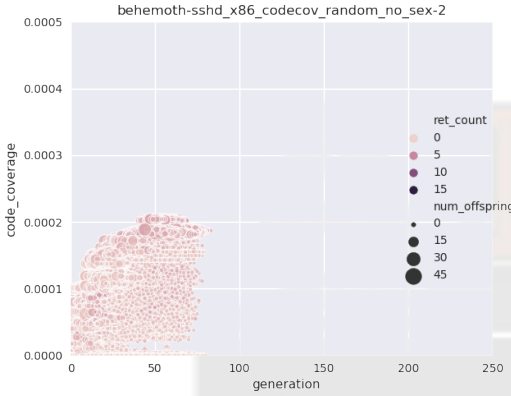
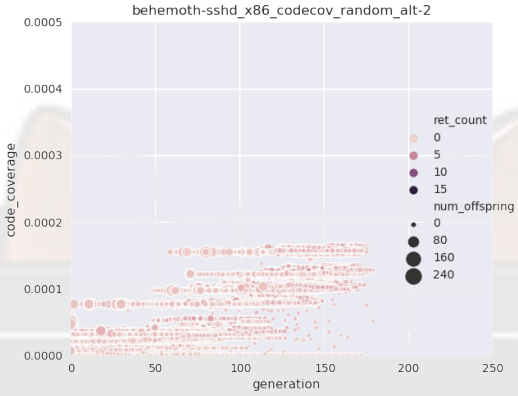
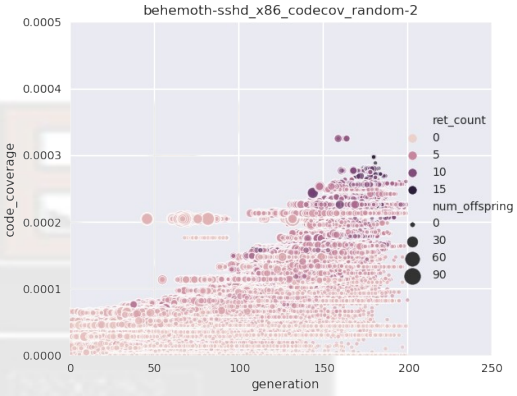
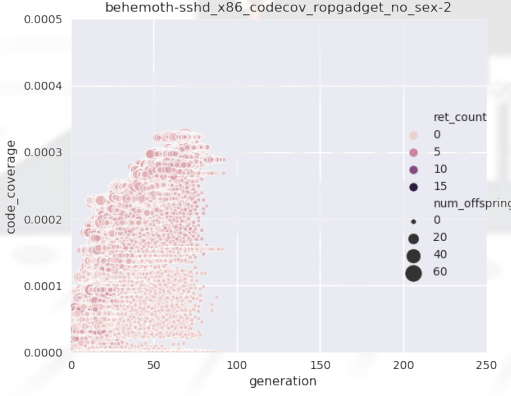
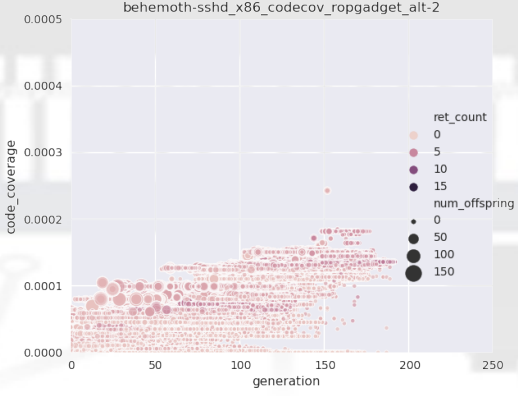
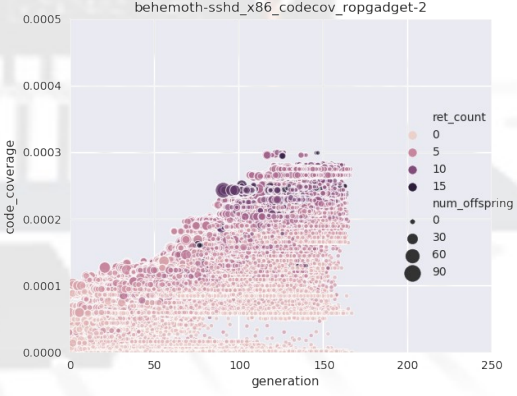












Experiment conclusions

Experiment conclusions

- Support for the *mixability theory of sexual reproduction?*
- Alternating crossover is not much better than asexual reproduction
- ROPgadget does not help asexual reproduction significantly
- Allele circulation is faster on single point crossover
- It is slowest with alternating crossover
- Higher return count correlates with code coverage

Register control

Register control

- Difficult to define proximity
  - Graph with state transitions: too expensive
  - Euclidean distance: too inaccurate
  - Hamming distance: too inaccurate
- How to handle indirections?
- How do we handle writable memory?

Register Control

- Weighted hamming distance
  - For each register and first m references:
    - Choose closest target, add 1 for each disagreement
    - Apply penalty if result is in different register
  - Sum all the results to get distance

Specimen #1

```
Name: wiles-flied-nooks-whipt, from island 0
Generation: 2736

Trace:
----
80b5dfa:        89 f0                                   mov eax, esi
80b5dfc:        8b 4c 24 54                             mov ecx, dword ptr [esp + 0x54]
80b5e00:        25 00 00 00 c0                          and eax, 0xc0000000
80b5e05:        01 c1                                   add ecx, eax
80b5e07:        03 44 24 58                             add eax, dword ptr [esp + 0x58]
80b5e0b:        81 e6 ff ff ff 3f                       and esi, 0x3fffffff
80b5e11:        89 c2                                   mov edx, eax
80b5e13:        74 39                                   je 0x80b5e4e
----
80b5e4e:        83 c4 3c                                add esp, 0x3c
80b5e51:        b8 01 00 00 00                          mov eax, 1
80b5e56:        5b                                      pop ebx
80b5e57:        5e                                      pop esi
80b5e58:        5f                                      pop edi
80b5e59:        5d                                      pop ebp
80b5e5a:        c3                                      ret
----
8075df7:        52                                      push edx
8075df8:        1c f6                                   sbb al, 0xf6
8075dfa:        c2 02 74                                ret 0x7402


Spidered register state:
EAX: 0xb
EBP: 0x81606d5 RX -> 0x312e2520 " %.1"
EBX: 0x81606a8 RX -> 0x6e69622f "/bin"
ECX: 0x8049633 RX -> 0x0
EDX: 0x0
EIP: 0x8075dfa RX -> 0xe7402c2
ESP: 0x8218150 RW (stack) -> 0x0
```

Specimen #2

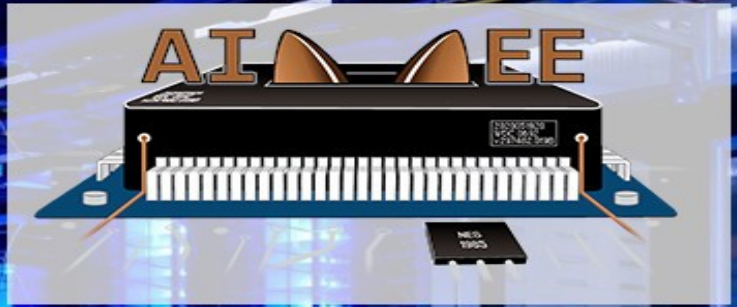
```
Name: corms-taxis-magma-wefts, from island 4
Generation: 951

Trace:
----
80badf1:        83 fb ff                cmp ebx, -1
80badf4:        74 0f                   je 0x80bae05
80badf6:        8d 4b 10                lea ecx, [ebx + 0x10]
80badf9:        31 d2                   xor edx, edx
80badfb:        39 4c 24 5c             cmp dword ptr [esp + 0x5c], ecx
80badff:        0f 85 99 01 00 00       jne 0x80baf9e
80baf9e:        83 c4 3c                add esp, 0x3c
80bafa1:        89 d0                   mov eax, edx
80bafa3:        5b                      pop ebx
80bafa4:        5e                      pop esi
80bafa5:        5f                      pop edi
80bafa6:        5d                      pop ebp
80bafa7:        c3                      ret
----
80badf1:        83 fb ff                cmp ebx, -1
80badf4:        74 0f                   je 0x80bae05
80badf6:        8d 4b 10                lea ecx, [ebx + 0x10]
80badf9:        31 d2                   xor edx, edx
80badfb:        39 4c 24 5c             cmp dword ptr [esp + 0x5c], ecx
80badff:        0f 85 99 01 00 00       jne 0x80baf9e
80baf9e:        83 c4 3c                add esp, 0x3c
80bafa1:        89 d0                   mov eax, edx
80bafa3:        5b                      pop ebx
80bafa4:        5e                      pop esi
80bafa5:        5f                      pop edi
80bafa6:        5d                      pop ebp
80bafa7:        c3                      ret
----
80badf1:        83 fb ff                cmp ebx, -1
80badf4:        74 0f                   je 0x80bae05
80badf6:        8d 4b 10                lea ecx, [ebx + 0x10]
80badf9:        31 d2                   xor edx, edx
80badfb:        39 4c 24 5c             cmp dword ptr [esp + 0x5c], ecx
80badff:        0f 85 99 01 00 00       jne 0x80baf9e
80baf9e:        83 c4 3c                add esp, 0x3c
80bafa1:        89 d0                   mov eax, edx
80bafa3:        5b                      pop ebx
80bafa4:        5e                      pop esi
80bafa5:        5f                      pop edi
80bafa6:        5d                      pop ebp
80bafa7:        c3                      ret
----
8088fa1:        7d 94                   jge 0x8088f37
8088f37:        ac                      lodsb al, byte ptr [esi]
8088f38:        c3                      ret
```

```
Spidered register state:
EAX: 0xb
EBP: 0x81e9182 RX -> 0xe00c0002
EBX: 0x8189e76 RX -> 0x6e69622f "/bin"
ECX: 0x80482dd RX -> 0x0
EDX: 0x0
EIP: 0x8088f38 RX -> 0xf13101c3
ESP: 0x82181f4 RW (stack) -> 0x80ad3ae RX -> 0x8b097400
```

Register Control

- Full solutions are rare (2 out of 10 trials with 1000 epochs)
- Required applying secondary novelty pressure
  - Count-min-sketch used to weight errors (so new errors are less important)
- Push VM did not prove better than bare ROP chains



Current status

ROPER 3: Slothrop

- Moving over to Julia
  - A robust scientific computing ecosystem
  - Interoperability with C(++) and Python
    - Writing Julia bindings for Unicorn was a pleasant experience
  - Makes for a good lingua franca, and facilitates collaboration
- Focusing on support for large populations, distributed over a network, rather than on single-host, efficiently threaded nodes

Next Steps: Problem

- Genetic programming is extremely effective, but uses a naive encoding of strings
- Strings are encoded as categorical data with distance/similarity a function of **string edit distance**
- “cat” → neighbors → “cot” - this doesn't reflect similarities in the meaning of the words
- With machine instructions, memory-adjacent machine instructions *can* have similar effects (or “meaning”) but this is far from guaranteed

Next Steps: Intuition

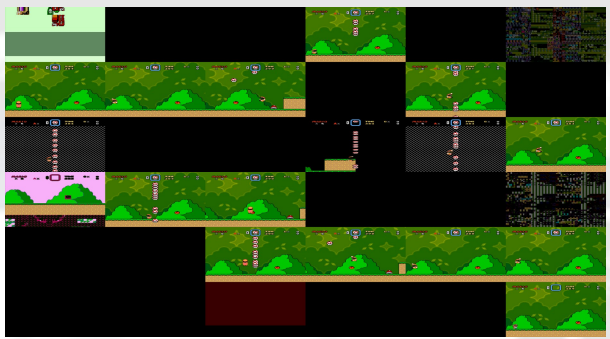
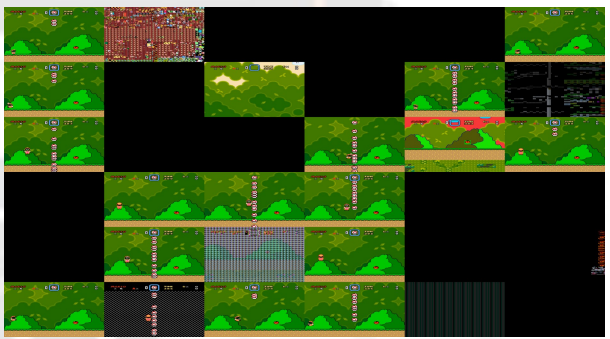
- Deep Learning already has an unreasonably effective solution to this problem: namely **Word2Vec**
- Word2Vec learns a vector representation of words that reflects their **contextual** similarity and difference
- This allows for **analogical reasoning** with extremely simple vector operations

Next Steps: Solution

- **Goal:** Reduce the amount of time for convergence in symbolic regression and increase transferability of solution
- Bootstrap an encoding by creating labeled data through the original genetic programming process, learn context
- Then switch to performing symbolic regression on the discovered latent space

Mario project

- Attempt at generalizing current results
- AI targets memory corruption glitches
- AI being used to automate exploitation (from induced weird states) in old videogames

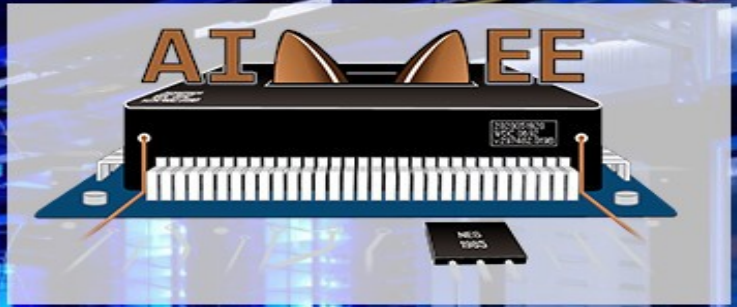




Schedule

- Jan 2021 Demonstrate generalized design against other systems (Mario project)
- March 2021 Final report
- June 2021 Academic papers submitted

Sources

- October report (and a lot of other information) on https://github.com/oblivia-simplex/berbalang/blob/master/org/october_report.org
- Berbalang source code: https://github.com/oblivia-simplex/berbalang
- Slothrop source code: https://github.com/oblivia-simplex/slothrop
- Thread-safe fork of Unicorn: https://github.com/oblivia-simplex/unicorn
- Julia Unicorn bindings: https://github.com/oblivia-simplex/unicorn-jl



Questions?

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