

Supplementary Information for *Nature* article by Lenski, Ofria, Pennock & Adami on "The Evolutionary Origin of Complex Features" (2003)

The first three sections below provide some background information on Avida and the logic functions that digital organisms perform. The fourth section provides some additional data on phenotypic and genomic evolution along the line of descent in the case-study population, up to the time of origin of the EQU function.

The Avida program and configuration files used in our experiments can be obtained free at myxo.css.msu.edu/papers/nature2003/. One can also view more background information about Avida as well as additional data from our experiments.

I. Avida instruction set

Each position in the genome sequence of a digital organism is one of 26 possible instructions. The table below shows the alphabetical code for each instruction, its mnemonic, and a brief description of its function.

(a) nop-A	No-operation instruction; modifies other instructions
(b) nop-B	No-operation instruction; modifies other instructions
(c) nop-C	No-operation instruction; modifies other instructions
(d) if-n-eq	Test if two registers contain equal values
(e) if-less	Test if one register contains a lesser value than another
(f) pop	Remove a number from a stack and place it in a register
(g) push	Copy the value of a register onto the top of a stack
(h) swap-stk	Toggle the active stack
(i) swap	Swap the contents of two specified registers
(j) shift-r	Shift all the bits on a register one to the right
(k) shift-l	Shift all the bits on a register one to the left
(l) inc	Increment a register
(m) dec	Decrement a register
(n) add	Calculate the sum of the values in two registers
(o) sub	Calculate the difference between the values in two registers
(p) nand	Perform a bitwise NAND on the values in two registers
(q) IO	Output the value in a register and replace with a new input
(r) h-alloc	Allocate memory for an offspring
(s) h-divide	Divide off an offspring contained in memory (specified by heads)
(t) h-copy	Make a copy of a single instruction in memory (specified by heads)
(u) h-search	Find a pattern of nop-instruction in the genome
(v) mov-head	Move a head to point to the same position as the flow-head
(w) jmp-head	Move a head by a fixed amount stored in a register

- (x) get-head Write the position of a specified head into a register
 (y) if-label Test if a specified pattern of nops has recently been copied
 (z) set-flow Move the flow-head to a specified position in memory

II. One- and two-input logic operations

There are two distinct one-input logic operations and eight distinct two-input operations. The tables below show the output obtained by performing these operations on each possible bit-wise input. The bottom rows indicate the minimum number of nand computations required to perform each operation, proven through exhaustive search. To receive the reward for doing a particular logic function, a digital organism must return the correct values for an entire series of 32 bit-wise problems, including multiple examples of each possible combination of inputs.

1-Input			2-Input										
Output			Output										
A	ECHO	NOT	A	B	NAND	AND	OR_N*	OR	AND_N*	NOR	XOR	EQU	
0	0	1	0	0	1	0	1	0	0	1	0	1	
1	1	0	0	1	1	0	0	1	0	0	1	0	
			1	0	1	0	1	1	1	0	1	0	
			1	1	0	1	1	1	0	0	0	1	
# nand	0	1	# nand		1	2	2	3	3	4	4	5	

* The order of the two inputs is arbitrary. Thus, the rewards for performing OR_N and AND_N are triggered by the reciprocal operations, in which A and B are reversed.

III. Shortest hand-written EQU program

The following hand-written program appears to be the shortest one using the set of available instructions that performs the EQU function, and that does not depend on the initial content of stacks and registers (whose initial contents are represented by '?' below). However, it has not been proven that this is the shortest program. Also, this program does not encode self-replication, but only performs the EQU function.

EQU						
#	Inst	AX	BX	CX	Stack	Output
1	IO	?	X	?	?	?
2	IO	?	X	Y	?	?

11	734	0	0	0	0	0	0	0	0	0	1.00	rucavcozcccccccccccccccamxecqcnchccccqcutycastvab
12	775	0	0	0	0	0	0	0	0	0	1.00	rucavcozcccccccccccccccamxecqcnchccccqcutycastvab
13	793	0	0	0	0	0	0	0	0	0	0.99	rucavcozccccsciccccccccccccamxecqcnchccccqcutycastvab
14	835	0	0	0	0	0	0	0	0	0	1.00	rucavcozccccsciccccccccccccamxelqcnchccccqcutycastvab
15	949	0	0	0	0	0	0	0	0	0	1.00	rucavcozjccsciccccccccccccamxelqcnchccccqcutycastvab
16	963	0	0	0	0	0	0	0	0	0	0.99	rucavcozjccsciccccccccccccamxelqcnqhccccqcutycastvab
17	1118	0	1	0	0	0	0	0	0	0	2.01	rucavcozjccsciccccccccccccamxelqcnqhccpcqcutycastvab
18	1194	0	1	0	0	0	0	0	0	0	1.01	rucavcotzjccsciccccccccccccamxelqcnqhccpcqcutycastvab
19	1250	0	1	0	0	0	0	0	0	0	1.01	rucavcotzjcisciccccccccccccamxelqcnqhccpcqcutycastvab
20	1252	0	0	0	1	0	0	0	0	0	2.01	rucavcotzjcisciccccccccccccamxelqcnqhpcpcqcutycastvab
21	1263	0	0	0	1	0	0	0	0	0	1.00	rucavcotzjcisciccccnccccckcamqelqcnqhpcpcqcutycastvab
22	1289	0	1	0	1	0	0	0	0	0	2.00	rucavcotzjcisciccccnccccckcamqelqcpqhpcpcqcutycastvab
23	1325	0	1	0	1	0	0	0	0	0	1.00	rucavcotzjcisciccdnccccckcamqelqcpqhpcpcqcutycastvab
24	1433	0	1	0	1	0	0	0	0	0	0.99	rucavcotzjcisciccdnceccccckcamqelqcpqhpcpcqcutycastvab
25	1439	0	1	0	1	0	0	0	0	0	1.15	rucavcotzjcisciccdnceccccckcamqelqcpqhpcpcqcutycastvab
26	1455	0	1	0	1	0	0	0	0	0	0.99	rucavcotzjcisciccdnceccccckramqelqcpqhpcpcqcutycastvab
27	1645	0	1	0	1	0	0	0	0	0	1.01	rucavcotzjaisciccdnceccccckramqelqcpqhpcpcqcutycastvab
28	1910	0	1	0	1	0	0	0	0	0	1.00	rucavcotzjaisciccdncecccccyramqelqcpqhpcpcqcutycastvab
29	1947	0	1	0	1	0	0	0	0	0	0.98	rucavcotzsaisciccdncecccccyramqelqcpqhpcpcqcutycastvab
30	2286	0	1	0	1	0	0	0	0	0	1.01	rucavcotzsaisciccdnceiccyramqelqcpqhpcpcqcutycastvab
31	2479	0	1	0	1	0	0	0	0	0	1.00	rucavcotzsaajsciccdnceiccyramqelqcpqhpcpcqcutycastvab
32	2669	0	1	0	1	0	0	0	0	0	1.00	rucavcotdsajsciccdnceiccyramqelqcpqhpcpcqcutycastvab
33	2711	0	1	0	1	0	0	0	0	0	1.01	rucavcotdajsciccdnceiccyramqelqcpqhpcpcqcutycastvab
34	2786	1	1	0	1	0	0	0	0	0	2.00	rucavcotdajsciccdnceiccyramqelqcpqhpcpcqcutycastvab
35	2828	1	1	0	1	0	0	0	0	0	1.00	rucavcotdqaqsciccdnceiccyramqelqcpqhpcpcqcutycastvab
36	2830	1	1	0	1	0	0	0	0	0	0.99	rucavcotdqaqsciccdnceiccyramqelqcpqhpcpcqcutycastvab
37	2987	1	1	0	1	0	0	0	0	0	1.00	rucavcotdqaqsciccdnceiccyramqetqcpqhpcpcqcutycastvab
38	3420	1	1	0	1	0	0	0	0	0	1.03	rucavcotdqaqsciccdnceiccyramqetqcpqhpcpcqcutycastvab
39	3551	1	1	0	1	0	0	0	0	0	1.00	rucavcitdqaqsciccdnceiccyramqetqcpqhpcpcqcutycastvab
40	3808	0	1	1	1	0	0	0	0	0	2.00	rucavcitdqaqsciccdnceiccyramqetqcpqhpcpcqcutycastvab
41	3914	0	1	1	1	0	0	0	0	0	1.01	rucavcitdqaqsciccdnceiccyramqetqcpqhpcpcqcutycastvab
42	3939	0	1	1	1	0	1	0	0	0	8.00	rucavcitdqaqsciccdnceiccyramqetqcpqhpcpcqcutycastvab
43	4190	0	1	1	1	0	1	0	0	0	1.00	rucavcotdqaqsciccdnceiccyramqetqcpqhpcpcqcutycastvab
44	4646	0	1	1	1	0	1	0	0	0	1.08	rucavcotdqaqsciccdnceiccyramqetqcpqhpcpcqcutycastvab
45	5292	0	1	1	1	0	1	0	0	0	1.00	rucavcotdqaqsciccdnceiccyramqetqcpqhpcpcqcutycastvab
46	5302	0	1	1	1	0	1	0	0	0	1.00	rucavcotdqaqsciccdnceiccyramqetqcpqhpcpcqcutycastvab
47	5323	0	1	1	1	0	1	0	0	0	0.99	ruzavcotdqaqsciccdnceiccyramqetqcpqhpcpcqcutycastvab
48	5337	0	1	1	1	0	1	0	0	0	0.99	ruzavcotdqaqsciccdnceiccyramqetqcpqhpcpcqcutycastvab
49	5481	0	1	1	1	0	1	0	0	0	1.02	ruzavcotcqaqsciccdnceiccyramqetqcpqhpcpcqcutycastvab
50	6067	0	1	1	1	0	1	0	0	0	1.00	ruzavcotiqaqsciccdnceiccyramqetqcpqhpcpcqcutycastvab
51	6200	0	1	1	1	0	1	0	0	0	1.00	ruzavcotizaqsciccdnceiccyramqetqcpqhpcpcqcutycastvab
52	6520	0	1	1	1	0	1	0	0	0	1.01	ruzavcotizaqsciccdnceiccyramqetqcpqhpcpcqcutycastvab
53	6765	0	1	1	1	0	1	0	0	0	1.00	rjzavcotizaqsciccdnceiccyramqetqcpqhpcpcqcutycastvab
54	7117	0	1	1	1	0	1	0	0	0	1.01	rjzavcotizaqsciccdnceiccyramqetqcpqhpcpcqcutycastvab
55	7478	0	1	1	1	0	1	0	0	0	1.00	rmzavcottizaqsciccdnceiccyramqetqcpqhpcpcqcutycastvab
56	7565	0	1	0	1	0	1	1	0	0	4.00	rmzavcottizaqsciccdnceiccyramqetqcpqhpcpcqcutycastvab
57	7977	0	1	0	1	0	1	1	0	0	1.01	rmzavcottizaqsciccdnceiccyramqetqcpqhpcpcqcutycastvab
58	8443	0	1	0	1	0	1	1	0	0	0.99	rmzavcottizaqsciccdnceiccyramqetqcpqhpcpcqcutycastvab
59	8742	0	1	0	1	0	1	1	0	0	0.99	rmzavcottizpqpqsciccdnceiccyramqetqcpqhpcpcqcutycastvab
60	8777	0	1	0	1	0	1	1	0	0	1.00	rmzavcothtizpqpqsciccdnceiccyramqetqcpqhpcpcqcutycastvab
61	9399	1	1	0	1	0	1	1	0	0	1.98	rmzavcotthi qpqpqsciccdnceiccyramqetqcpqhpcpcqcutycastvab
62	9428	1	1	0	1	0	1	1	0	0	1.00	rmzavcotthi qpqpqsciccdnceiccyramqetqcpqhpcpcqcutycastvab
63	9582	1	1	0	1	0	1	1	0	0	0.32	rmzavcotthi qpqpqsciccdnceiccyramqetqcpqhpcpcqcutycastvab
64	9590	1	1	0	1	0	1	1	0	0	3.19	rmzavcotthi qpqpqsciccdnceiccyramqetqcpqhpcpcqcutycastvab
65	9823	1	1	0	1	0	1	1	0	0	1.00	rmzavcotthi qpqpqsciccdnceiccyramqetqcpqhpcpcqcutycastvab
66	9993	1	1	0	1	0	1	1	0	0	1.00	rmzavcotthi qpqpqsciccdnceiccyramqetqcpqhpcpcqcutycastvab
67	11029	1	1	0	1	0	1	1	0	0	1.01	rmzavcotthi qpqpqsciccdnceiccyramqetqcpqhpcpcqcutycastvab
68	11584	1	1	0	1	0	1	1	0	0	1.01	rmzavcotthi qpqpqsciccdnceiccyramqetqcpqhpcpcqcutycastvab
69	12028	1	1	0	1	0	1	1	0	0	1.01	rmzavcotthi qpqpqsciccdnceiccyramqetqcpqhpcpcqcutycastvab
70	12671	1	1	0	1	0	1	1	0	0	1.01	rmzavcotthi qpqpqsciccdnceiccyramqetqcpqhpcpcqcutycastvab
71	12853	1	1	0	1	0	1	1	0	0	1.00	rmzavcotthi qpqpqsciccdnceiccyramqetqcpqhpcpcqcutycastvab
72	12947	1	1	0	1	0	1	1	0	0	0.99	rmzavcotthi qpqpqsciccdnceiccyramqetqcpqhpcpcqcutycastvab
73	13119	1	1	0	1	0	1	1	0	0	1.00	rmzavcotthi qpqpqsciccdnceiccyramqetqcpqhpcpcqcutycastvab
74	13537	1	1	0	1	0	1	1	0	0	1.00	rmzavcotthi qpqpqsciccdnceiccyramqetqcpqhpcpcqcutycastvab

75	13557	1	1	0	1	0	1	1	0	0	1.00	rmzavcztnbiqptqpqcpcctltnncorctdpamqstqcpqpdgpcqcutycastttvab
76	13869	1	1	0	1	0	1	1	0	0	1.00	rmzavcztnbiqptqpqcpcctltnncorctdpamqdtqcpqpdgpcqcutycastttvab
77	13952	1	1	0	1	0	1	1	0	0	1.01	rmzavcztnbiqptqpqcpcctltnncorctdpamqdtqcpqpdhpcqcutycastttvab
78	14478	1	1	0	1	0	1	1	0	0	1.00	rmzavcztnbiqptqpqcpcctltnncorctdpamqdtqcpqpcbpqcutycastttvab
79	15603	1	1	0	1	0	1	1	0	0	1.00	rmzavcztwbiqptqpqcpcctltnncorctdpamqdtqcpqpcbpqcutycastttvab
80	15769	1	1	0	1	0	1	1	0	0	1.01	rmzavcztwbiqptqpqcpcctltnncogctdpamqdtqcpqpcbpqcutycastttvab
81	15936	1	1	0	1	0	1	1	0	0	1.00	rmzavcztwbiqptqpqcpcctltnncogctbpamqdtqcpqpcbpqcutycastttvab
82	16039	1	1	0	1	0	1	1	0	0	1.00	rmzavcztwbiqptqpqcpcctltnncogctbnamqdtqcpqpcbpqcutycastttvab
83	16090	1	1	0	1	0	1	1	0	0	1.00	rmzavcztwbiqptqpqcpcctltnncogctbnamqdtqcpqpihpcqcutycastttvab
84	16672	1	1	0	1	0	1	1	0	0	0.93	rmzavcztwbiqptqpqcpcctltnncogctbnamqdtqcpqpihpcqcutycastt_vab
85	16769	1	1	0	0	1	1	1	0	0	1.98	rmzavcztwbiqptqpqcpcctltnncogctbnamqdtqcpqpihpcqcutycastttvab
86	16786	1	1	0	0	1	1	1	0	0	0.99	rmzavcztwbiqptqpqcpcctltnncogctbnamqdtqcpqpihpcqcutycastttvab
87	16900	1	0	0	1	1	1	1	0	0	2.00	rmzavcztwbiqptqpqcpcctltnncogctbnamqdtqcpqpihpcqcutycastttvab
88	16979	1	0	0	1	1	1	1	0	0	1.08	rmzavcztwbiqptqpqcpcctltnncogctbnamqdtqcpqpihpcqcutycastttvab
89	17008	1	0	0	1	1	1	1	0	0	1.00	rmzavcztgbiqptqpqcpcctltnncogctbnamqdtqcpqpihpcqcutycastttvab
90	17145	1	0	0	1	1	1	1	0	0	1.00	rmzavcjtgbiqptqpqcpcctltnncogctbnamqdtqcpqpihpcqcutycastttvab
91	17370	1	0	0	1	1	1	1	0	0	1.01	rmzavcjtgbiqptqpqcpcctltnncogctbnamqdtqcpqpihpcqcutycastttvab
92	19260	1	0	0	1	1	1	1	0	0	1.01	rmzavcjtgbiqptqpqcpcctltnncogctbnamqdtqcptepifpqtqcutycastttvab
93	19828	1	0	0	1	1	1	1	0	0	1.00	rmzavcjtgbiqptqpqcpcctltnncogctbnamqdtqcptipifpqtqcutycastttvab
94	20740	1	0	0	1	1	1	1	0	0	0.99	rmzavcjtgbiqptqpqcpcctltnncogctbnamqdtqcptipifpq_qcutycastttvab
95	20804	1	0	0	1	1	1	1	0	0	1.00	rmzavcjtgciqptqpqcpcctltnncogctbnamqdtqcptipifpqtqcutycastttvab
96	21032	1	1	0	1	1	1	1	0	0	2.00	rmzavcjtdciqptqpqcpcctltnncogctbnamqdtqcptipqfpqqcutycastttvab
97	21509	1	1	0	1	1	1	1	0	0	1.00	rmzavcjtzciqptqpqcpcctltnncogctbnamqdtqcptipqfpqqcutycastttvab
98	22229	1	1	0	1	1	1	1	0	0	1.00	rmzavcatzciqptqpqcpcctltnncogctbnamqdtqcptipqfpqqcutycastttvab
99	22240	1	1	0	1	1	1	1	0	0	1.00	rmzavcgtzciqptqpqcpcctltnncogctbnamqdtqcptipqfpqqcutycastttvab
100	22404	1	1	1	1	1	1	1	0	0	2.90	rmzavcgtzciqptqpqcpcctltnncogctbnamqdtqcptipqfpqqcutycuastttvab
101	22412	1	1	1	1	1	1	1	0	0	1.00	rmzavcgtzciqptqpqcpcctltnncogctbnamqdtqcptipqfpqqcutycuastttva_
102	22487	1	1	1	1	1	1	1	0	0	1.00	rmzavcgtmciqptqpqcpcctltnncogctbnamqdtqcptipqfpqqcutycuastttva
103	22586	1	1	1	1	1	1	1	0	0	0.99	rmzavcg_mciqptqpqcpcctltnncogctbnamqdtqcptipqfpqqcutycuastttva
104	22629	1	1	1	1	1	1	1	0	0	1.05	rmzavcgmcicqptqpqcpcctltnncogctbnamqdtqcptipqfpqqcutycuastttva
105	22864	1	1	1	1	1	1	1	0	0	1.00	rmzavcgmcicqptqpqcpcctltnncogctbkamqdtqcptipqfpqqcutycuastttva
106	22886	1	1	1	1	1	1	1	0	0	0.99	rmzavcgmcicqptqpqcpcctltnncogc_bkamqdtqcptipqfpqqcutycuastttva
107	23002	1	1	1	1	1	1	1	0	0	1.02	rmzavcgmcicqptqpqcpcctltnncogcbkamqdtqcptipqfpqqcutycuastttva
108	25881	1	1	1	1	1	1	1	0	0	1.00	rmzavcgmcicqptqpqcpcctltnncogcbkamqdtqcptipqfpqqcutycuastttva
109	26343	1	1	1	1	1	1	1	0	0	1.01	rmzavcgmcicqptqpqcpcctltnncogcbeamqdtqcptipqfpqqcutycuastttva
110	27437	1	0	1	1	1	1	1	0	0	0.49	rmzavcgmcicqptqpqcpcctltnncogcbeamqdtqcptipqfpqqxutycuastttva
111	27450	1	0	0	1	1	1	1	0	1	8.00	rmzavcgmcicqptqpqcpcctltnncogcbeamqdtqcptipqfpqgqutycuastttva