Supporting Information

Nano-Encrypted Morse Code: A Versatile Approach to Programmable and Reversible Nanoscale Assembly and Disassembly

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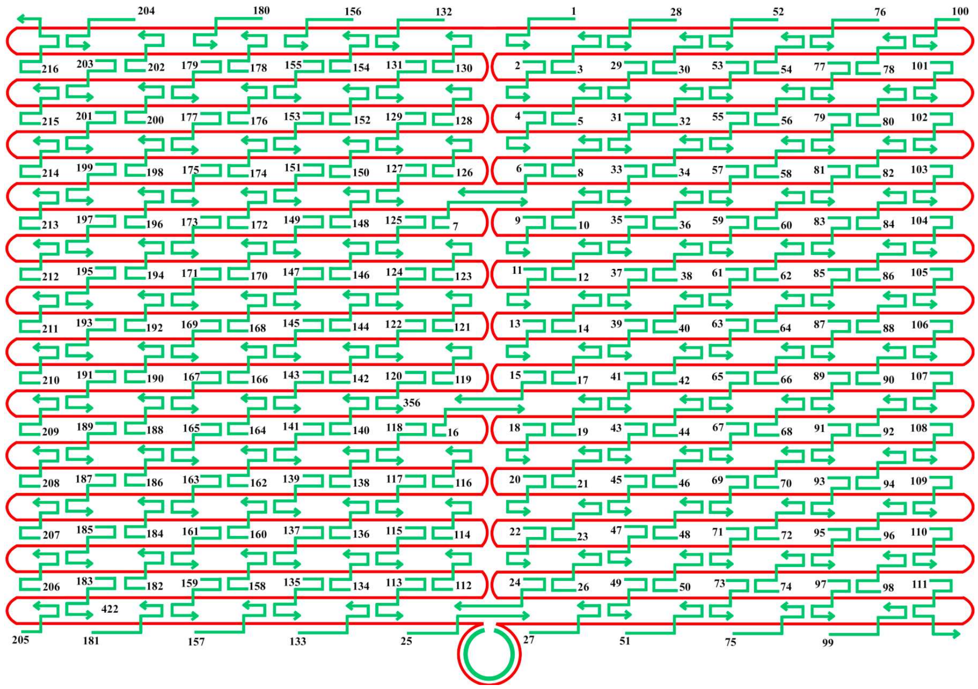
1. Experimental

1.1 Chemicals and Materials

All Oligonucleotides used in the current study were purchased from Integrated DNA Technologies (Coralville, IA). M13 viral DNA was purchased from New England Biolabs, Inc. (#N4040S, NEB). Tributylphosphine solution (200 mM, in N-methyl-2-pyrrolidinone; Sigma-Aldrich), Desthiobiotin polyethyleneoxide Iodoacetamide (>90%, Sigma-Aldrich), Avidin agarose (6% beaded agarose, Thermo Scientific) Amicon centrifugal filter units (100,000 MWCO, Millipore). All buffer components were purchased from Sigma Aldrich unless otherwise noted.

1.2 Origami Design[1,2]



Sequence Name	Sequence
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2	AATGCCCCGTAACAGT GCCCGTATCTCCCTCA
3	TGCCTTGACTGCCTAT TTCGGAACAGGGATAG
4	GAGCCGCCCCACCACC GGAACCGCGACGGAAA
5	AACCAGAGACCCTCAG AACCGCCAGGGGTCAG
6	TTATTCATAGGGAAGG TAAATATT CATTCAGT
7	CATAACCCGAGGCATA GTAAGAGC TTTTTAAG
8	ATTGAGGGTAAAGGTG AATTATCAATCACCGG
9	AAAAGTAATATCTTAC CGAAGCCCTTCCAGAG
10	GCAATAGCGCAGATAG CCGAACAATTCAACCG
11	CCTAATTTACGCTAAC GAGCGTCTAATCAATA
12	TCTTACCAGCCAGTTA CAAAATAAATGAAATA
13	ATCGGCTGCGAGCATG TAGAAACCTATCATAT
14	CTAATTTATCTTTCCT TATCATTCATCCTGAA
15	GCGTTATAGAAAAAGC CTGTTTAG AAGGCCGG
16	GCTCATTTTCGCATTA AATTTTTG AGCTTAGA
17	AATTACTACAAATTCT TACCAGTAATCCCATC
18	TTAAGACGTTGAAAAC ATAGCGATAACAGTAC
19	TAGAATCCCTGAGAAG AGTCAATAGGAATCAT
20	CTTTTACACAGATGAA TATACAGTAAACAATT

21	TTTAACGTTCGGGAGA AACAATAATTTTCCCT
22	CGACAACTAAGTATTA GACTTTACAATACCGA
23	GGATTTAGCGTATTAA ATCCTTTGTTTTCAGG
24	ACGAACCAAAACATCG CCATTAAA TGGTGGTT
25	GAACGTGGCGAGAAAG GAAGGGAA CAAACTAT
26	TAGCCCTACCAGCAGA AGATAAAAACATTTGA
27	CGGCCTTGCTGGTAAT ATCCAGAACGAACTGA
28	CTCAGAGCCACCACCC TCATTTTCCTATTATT
29	CTGAAACAGGTAATAA GTTTTAACCCCTCAGA
30	AGTGTACTTGAAAGTA TTAAGAGGCCGCCACC
31	GCCACCACTCTTTTCA TAATCAAACCGTCACC
32	GTTTGCCACCTCAGAG CCGCCACCGATACAGG
33	GACTTGAGAGACAAAA GGGCGACAAGTTACCA
34	AGCGCCAACCATTTGG GAATTAGATTATTAGC
35	GAAGGAAAATAAGAGC AAGAAACAACAGCCAT
36	GCCCAATACCGAGGAA ACGCAATAGGTTTACC
37	ATTATTTAACCCAGCT ACAATTTTCAAGAACG
38	TATTTTGCTCCCAATC CAAATAAGTGAGTTAA
39	GGTATTAAGAACAAGA AAAATAATTAAAGCCA
40	TAAGTCCTACCAAGTA CCGCACTCTTAGTTGC
41	ACGCTCAAAATAAGAA TAAACACCGTGAATTT
42	AGGCGTTACAGTAGGG CTTAATTGACAATAGA
43	ATCAAAATCGTCGCTA TTAATTAACGGATTCG
44	CTGTAAATCATAGGTC TGAGAGACGATAAATA
45	CCTGATTGAAAGAAAT TGCGTAGACCCGAACG
46	ACAGAAATCTTTGAAT ACCAAGTTCCTTGCTT
47	TTATTAATGCCGTCAA TAGATAATCAGAGGTG
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52	CCCTCAGAACCGCCAC CCTCAGAACTGAGACT
53	CCTCAAGAATACATGG CTTTTGATAGAACCAC
54	TAAGCGTCGAAGGATT AGGATTAGTACCGCCA
55	CACCAGAGTTCGGTCA TAGCCCCCGCCAGCAA
56	TCGGCATTCCGCCGCC AGCATTGACGTTCCAG
57	AATCACCAAATAGAAA ATTCATATATAACGGA
58	TCACAATCGTAGCACC ATTACCATCGTTTTCA
59	ATACCCAAGATAACCC ACAAGAATAAACGATT
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61	TTTTGTTTAAGCCTTA AATCAAGAATCGAGAA

62	AGGTTTTGAACGTCAA AAATGAAAGCGCTAAT
63	CAAGCAAGACGCGCCT GTTTATCAAGAATCGC
64	AATGCAGACCGTTTTT ATTTTCATCTTGCGGG
65	CATATTTAGAAATACC GACCGTGTTACCTTTT
66	AATGGTTTACAACGCC AACATGTAGTTCAGCT
67	TAACCTCCATATGTGA GTGAATAAACAAAATC
68	AAATCAATGGCTTAGG TTGGGTTACTAAATTT
69	GCGCAGAGATATCAAA ATTATTTGACATTATC
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71	ATTTTGCGTCTTTAGG AGCACTAAGCAACAGT
72	CTAAAATAGAACAAAG AAACCACCAGGGTTAG
73	GCCACGCTATACGTGG CACAGACAACGCTCAT
74	GCGTAAGAGAGAGCCA GCAGCAAAAAGGTTAT
75	GGAAATACCTACATTT TGACGCTCACCTGAAA
76	TATCACCGTACTCAGG AGGTTTAGCGGGGTTT
77	TGCTCAGTCAGTCTCT GAATTTACCAGGAGGT
78	GGAAAGCGACCAGGCG GATAAGTGAATAGGTG
79	TGAGGCAGGCGTCAGA CTGTAGCGTAGCAAGG
80	TGCCTTTAGTCAGACG ATTGGCCTGCCAGAAT
81	CCGGAAACACACCACG GAATAAGTAAGACTCC
82	ACGCAAAGGTCACCAA TGAAACCAATCAAGTT
83	TTATTACGGTCAGAGG GTAATTGAATAGCAGC
84	TGAACAAACAGTATGT TAGCAAACTAAAAGAA
85	CTTTACAGTTAGCGAA CCTCCCGACGTAGGAA
86	GAGGCGTTAGAGAATA ACATAAAAGAACACCC
87	TCATTACCCGACAATA AACAACATATTTAGGC
88	CCAGACGAGCGCCCAA TAGCAAGCAAGAACGC
89	AGAGGCATAATTTCAT CTTCTGACTATAACTA
90	TTTTAGTTTTTCGAGC CAGTAATAAATTCTGT
91	TATGTAAACCTTTTTT AATGGAAAAATTACCT
92	TTGAATTATGCTGATG CAAATCCACAAATATA
93	GAGCAAAAACTTCTGA ATAATGGAAGAAGGAG
94	TGGATTATGAAGATGA TGAAACAAAATTTCAT
95	CGGAATTATTGAAAGG AATTGAGGTGAAAAAT
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101	AGGGTTGA TTTT ATAAATCC TCATTAAATGATATTC
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103	AGCACCGT TTTT TAAAGGTG GCAACATAGTAGAAAA
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114	GCATAAAGTTCCACAC AACATACGAAGCGCCA
115	GCTCACAATGTAAAGC CTGGGGTGGGTTTGCC
116	TTCGCCATTGCCGGAA ACCAGGCATTAAATCA
117	GCTTCTGGTCAGGCTG CGCAACTGTGTTATCC
118	GTTAAAATTTTAACCA ATAGGAACCCGGCACC
119	AGACAGTCATTCAAAA GGGTGAGAAGCTATAT
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127	CCAAATCACTTGCCCT GACGAGAACGCCAAAA
128	CTCATCTTGAGGCAAA AGAATACAGTGAATTT
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131	TCGGTTTAGCTTGATA CCGATAGTCCAACCTA
132	TGAGTTTCGTCACCAG TACAAACTTAATTGTA
133	CCCCGATTTAGAGCTT GACGGGGAAATCAAAA
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135	GAGTTGCACGAGATAG GGTTGAGTAAGGGAGC
136	GTGAGCTAGTTTCCTG TGTGAAATTTGGGAAG
137	TCATAGCTACTCACAT TAATTGCGCCCTGAGA
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142	ACCGTTCTAAATGCAA TGCCTGAGAGGTGGCA
143	TATATTTTAGCTGATA AATTAATGTTGTATAA

144	TCAATTCTTTTAGTTT GACCATTACCAGACCG
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146	GAAGCAAAAAAGCGGA TTGCATCAGATAAAAA
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150	ACGAGTAGTGACAAGA ACCGGATATACCAAGC
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156	TGTAGCATTCCACAGA CAGCCCTCATCTCCAA
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159	AGCTGATTACAAGAGT CCACTATTGAGGTGCC
160	ACTGCCCGCCGAGCTC GAATTCGTTATTACGC
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175	CCAGGCGCTTAATCAT TGTGAATTACAGGTAG
176	CGCCTGATGGAAGTTT CCATTAAACATAACCG
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183	TGGTTTTTAACGTCAA AGGGCGAAGAACCATC
184	GCCAGCTGCCTGCAGG TCGACTCTGCAAGGCG

185	CTTGCATGCATTAATG AATCGGCCCGCCAGGG
186	ATTAAGTTCGCATCGT AACCGTGCGAGTAACA
187	TAGATGGGGGGTAACG CCAGGGTTGTGCCAAG
188	ACCCGTCGTCATATGT ACCCCGGTAAAGGCTA
189	CATGTCAAGATTCTCC GTGGGAACCGTTGGTG
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192	CAAAATTAAAGTACGG TGTCTGGAAGAGGTCA
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195	AAACAGTTGATGGCTT AGAGCTTATTTAAATA
196	ACTGGATAACGGAACA ACATTATTACCTTATG
197	ACGAACTAGCGTCCAA TACTGCGGAATGCTTT
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204	ACGTTAGTAAATGAAT TTTCTGTAAGCGGAGT
205	TTTT CGATGGCC CACTACGTAAACCGTC
206	TATCAGGG TTTT CGGTTTGC GTATTGGGAACGCGCG
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208	CACGACGT TTTT GTAATGGG ATAGGTCAAAACGGCG
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210	AGAGAATC TTTT GGTTGTAC CAAAAACAAGCATAAA
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212	ATATAATG TTTT CATTGAAT CCCCCTCAAATCGTCA
213	TAAATATT TTTT GGAAGAAA AATCTACGACCAGTCA
214	GGACGTTG TTTT TCATAAGG GAACCGAAAGGCGCAG
215	ACGGTCAA TTTT GACAGCAT CGGAACGAACCCTCAG
216	CAGCGAAAA TTTT ACTTTCA ACAGTTTCTGGGATTTTGCTAAAC TTTT
Loop1	AACATCACTTGCCTGAGTAGAAGAACT
Loop2	TGTAGCAATACTTCTTTGATTAGTAAT
Loop3	AGTCTGTCCATCACGCAAATTAACCGT
Loop4	ATAATCAGTGAGGCCACCGAGTAAAAG
Loop5	ACGCCAGAATCCTGAGAAGTGTTTTT
Loop6	TTAAAGGGATTTTAGACAGGAACGGT
Loop7	AGAGCGGGAGCTAAACAGGAGGCCGA
Loop8	TATAACGTGCTTTCCTCGTTAGAATC
Loop9	GTACTATGGTTGCTTTGACGAGCACG

Loop10	GCGCTTAATGCGCCGCTACAGGGCGC

1.3 DNA Sequences (Morse Code)

Thiol modified sequences:

Sequence Name	Sequence (5'-3')
HS-16	GCTCATTTTCGCATTA AATTTTTG AGCTTAGA
HS-32	GTTTGCCACCTCAGAG CCGCCACCGATACAGG
HS-38	TATTTTGCTCCCAATC CAAATAAGTGAGTTAA
HS-44	CTGTAAATCATAGGTC TGAGAGACGATAAATA
HS-56	TCGGCATTCCGCCGCC AGCATTGACGTTCCAG
HS-62	AGGTTTTGAACGTCAA AAATGAAAGCGCTAAT
HS-68	AAATCAATGGCTTAGG TTGGGTTACTAAATTT
HS-128	CTCATCTTGAGGCAAA AGAATACAGTGAATTT
HS-194	TTTTTGCGCAGAAAAC GAGAATGAATGTTTAG

Biotin modified sequences –

Sequence Name	Sequence (5'-3')
Bio-50	GAATGGCTAGTATTAA CACCGCCTCAACTAAT
Bio-74	GCGTAAGAGAGAGCCA GCAGCAAAAAGGTTAT
Bio-112	CCGAAATCCGAAAATC CTGTTTGAAGCCGGAA
Bio-123	TTTTAATTGCCCGAAA GACTTCAAAACACTAT
Bio-134	GAATAGCCGCAAGCGG TCCACGCTCCTAATGA
Bio-140	AAATAATTTTAAATTG TAAACGTTGATATTCA
Bio-146	GAAGCAAAAAAGCGGA TTGCATCAGATAAAAA
Bio-152	GCGAAACATGCCACTA CGAAGGCATGCGCCGA
Bio-182	TGGACTCCCTTTTCAC CAGTGAGACCTGTCGT
Bio-188	ACCCGTCGTCATATGT ACCCCGGTAAAGGCTA
Bio-200	GCTCCATGAGAGGCTT TGAGGACTAGGGAGTT
Bio-206	TATCAGGG TTTT CGGTTTGC GTATTGGGAACGCGCG
Bio-209	GATTGACC TTTT GATGAACG GTAATCGTAGCAAACA
Bio-212	ATATAATG TTTT CATTGAAT CCCCCTCAAATCGTCA
Bio-215	ACGGTCAA TTTT GACAGCAT CGGAACGAACCCTCAG

DNA Sequences (Big I)

Biotin modified sequences:

Sequence Name	Sequence (5'-3')
Bio-14	CTAATTTATCTTTCCT TATCATTCATCCTGAA
Bio-37	ATTATTTAACCCAGCT ACAATTTTCAAGAACG
Bio-40	TAAGTCCTACCAAGTA CCGCACTCTTAGTTGC
Bio-59	ATACCCAAGATAACCC ACAAGAATAAACGATT
Bio-61	TTTTGTTTAAGCCTTA AATCAAGAATCGAGAA
Bio-124	AAGAGGAACGAGCTTC AAAGCGAAGATACATT
Bio-144	TCAATTCTTTTAGTTT GACCATTACCAGACCG

Thiol modified sequences:

Sequence Name	Sequence (5'-3')
HS-11	CCTAATTTACGCTAAC GAGCGTCTAATCAATA
HS-57	AATCACCAAATAGAAA ATTCATATATAACGGA
HS-63	CAAGCAAGACGCGCCT GTTTATCAAGAATCGC
HS-65	CATATTTAGAAATACC GACCGTGTTACCTTTT
HS-121	TTTCATTTGGTCAATA ACCTGTTTATATCGCG
HS-147	TCAGAAGCCTCCAACA GGTCAGGATCTGCGAA
HS-164	CTTTCATCCCCAAAAA CAGGAAGACCGGAGAG
HS-166	GGTAGCTAGGATAAAA ATTTTTAGTTAACATC
HS-168	CAATAAATACAGTTGA TTCCCAATTTAGAGAG
HS-170	TACCTTTAAGGTCTTT ACCCTGACAAAGAAGT
HS-172	TTTGCCAGATCAGTTG AGATTTAGTGGTTTAA

1.3 Desthiobiotin modification of thiol-DNA

The concentration of DNA was calculated based on absorption at 280 nm according to the Beer-Lambert law. and adjusted to 100 µM. A 10 µM solution of 5` thiol modified DNA (used as received from IDT) was incubated with 2 µL of tributylphosphine solution for 2 hours at room temperature to the reduce the disulfide bond. Next, a 35 mM solution of desthiobiotin polyethyleneoxide iodoacetamide was freshly prepared in a 1 x TAE-Mg2+ buffer (Tris, 40 mM; acetic acid, 20 mM; EDTA, 2 mM; and magnesium acetate, 12.5 mM;

pH 8.0) and incubated for 5 hours at 50 °C. Excess linkers were removed by washing 10 times with water using a 30 MWCO Amicon centrifugal filter. To purify the desthiobiotin functionalized product, the washed and concentrated solution was incubated with avidin agarose beads and eluted following manufacturers suggested protocols.

1.4 Non-denaturing PAGE

Gels containing 4% polyacrylamide (19:1 acrylamide/ bisacrylamide) were run on an Owl Adj2 electrophoresis unit at 4 °C (4 W, constant wattage). The running buffer was 1x TAE-Mg^{2+} buffer. After electrophoresis, the gels were stained with ethidium bromide (Sigma) and imaged under UV illumination. DNA recovery was done by cutting and soaking gel pieces with 1x TAE-Mg^{2+} buffer for 12 hours at 4 °C.

1.5 Design and assembly of DNA origami

Rectangular origami tiles were formed according to Rothemund's paper with a ratio of 1:20 between viral DNA and both modified and unmodified staple strands. A concentration of 10 nM viral DNA was used in this work. Helper strands were mixed to form a master mix (50 μM) that was added to the viral DNA sequence in 1x TAE-Mg^{2+} buffer and annealed from 90 °C to 20 °C over 3 hours. After assembly of the origami tiles, they were washed 3x with 1x TAE-Mg^{2+} and concentrated using Amicon centrifugal filter units (100 MWCO, 300 x g speed, 10 min).

1.6 Conjugation of proteins to DNA origami template

To demonstrate selective release of protein from origami template, the protein decorated tiles were diluted to 1 mL and dialyzed overnight in a 300,000 MWCO membrane to remove the large excess of streptavidin that was necessary to prevent aggregation in the previous incubation step. The sample is then treated with 3 mM of biotin solution in 1x TAE-Mg^{2+} for 2 hours at room temperature before dialyzed with 1 mM biotin for 24 hours at 4 °C. The final solution is washed several times with 1x TAE-Mg^{2+} to remove excess biotin and concentrated to 30 µL using a 100,000 MWCO membrane.

1.7 AFM imaging

A drop of 3 ul DNA solution was spotted onto freshly cleaved mica surface, and kept for 10 s to achieve strong adsorption. 30 µL of 1x TAE-Mg^{2+} was added to the mica surface and the tip was pre-wet to prevent drift during imaging. Fluid imaging was performed using nitride probes having a resonance frequency of 21-52 kHz (Olympus -TR400PSA). The tip–surface interaction was minimized by optimizing the scan set-point to the highest possible value. AFM imaging was performed at 22 °C. AFM data was processed with IGOR Pro software.

1.8 References:

(1) Chhabra, R.; Sharma, J.; Ke, Y. G.; Liu, Y.; Rinker, S.; Lindsay, S.; Yan, H. *Journal of the American Chemical Society* **2007**, *129*, 10304.
(2) Rothemund, P. W. K. *Nature* **2006**, *440*, 297.