

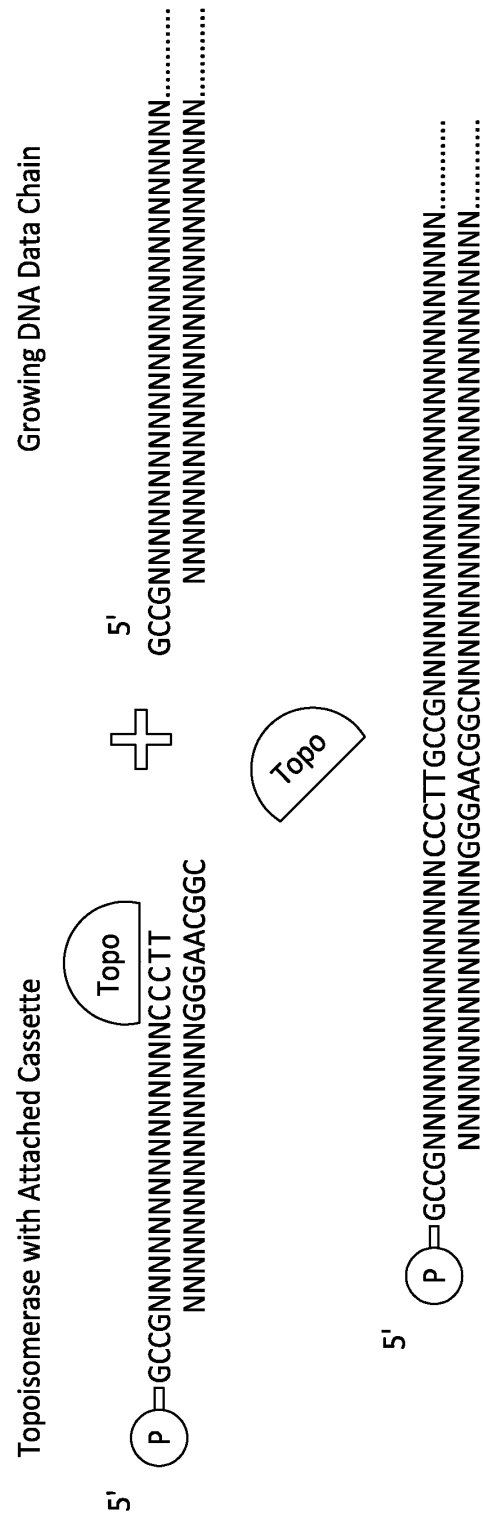


FIG. 1

1		0		0		1	
GCCG	NNNNNNNNNNNNNNNNNN	CCCTTGCCG	NNNN	CCCTTGCCG	NNNN	CCCTTGCCG	NNNNNNNNNNNNNNNN
	NNNNNNNNNNNNNNNNNN	GGGAACGGC	NNNN	GGGAACGGC	NNNN	GGGAACGGC	NNNNNNNNNNNNNNNN
		Spacer Region		Spacer Region		Spacer Region	

FIG. 2

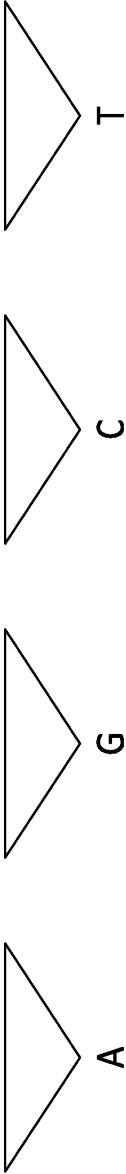
Two-bit, multi-base encoding
Example - 15 bases / 2 bits

C1	AAGGATTAGACTGGG	C5	ATCTGATGGAAGAA	C9	GAGCGCTACCCACAA	C13	CGAATATCTTAGTAT
C2	TGGGAGTAGACTGGT	C6	ATCGGATGACAGAA	C10	GAGCGCTACCCATAA	C14	CGAATACCCAGCGT
C3	CTGGACTAGACTGGA	C7	ATCTGATGTGTGAA	C11	GAGGGATAACAATAA	C15	CGAATAACAAAGAAAT
C4	TAGGACTAGACTAGA	C8	ATCGGATGAGCGAA	C12	GAGAGCTACCTAGAA	C16	CGAATAGCATAGCAT

Underlying binary code:

0	0	0	1	1	0	1	1
---	---	---	---	---	---	---	---

Two-bit, single base encoding
00 = A, 01 = G, 10 = C, 11 = T



Substituting any single base will change the underlying binary code represented

FIG. 4

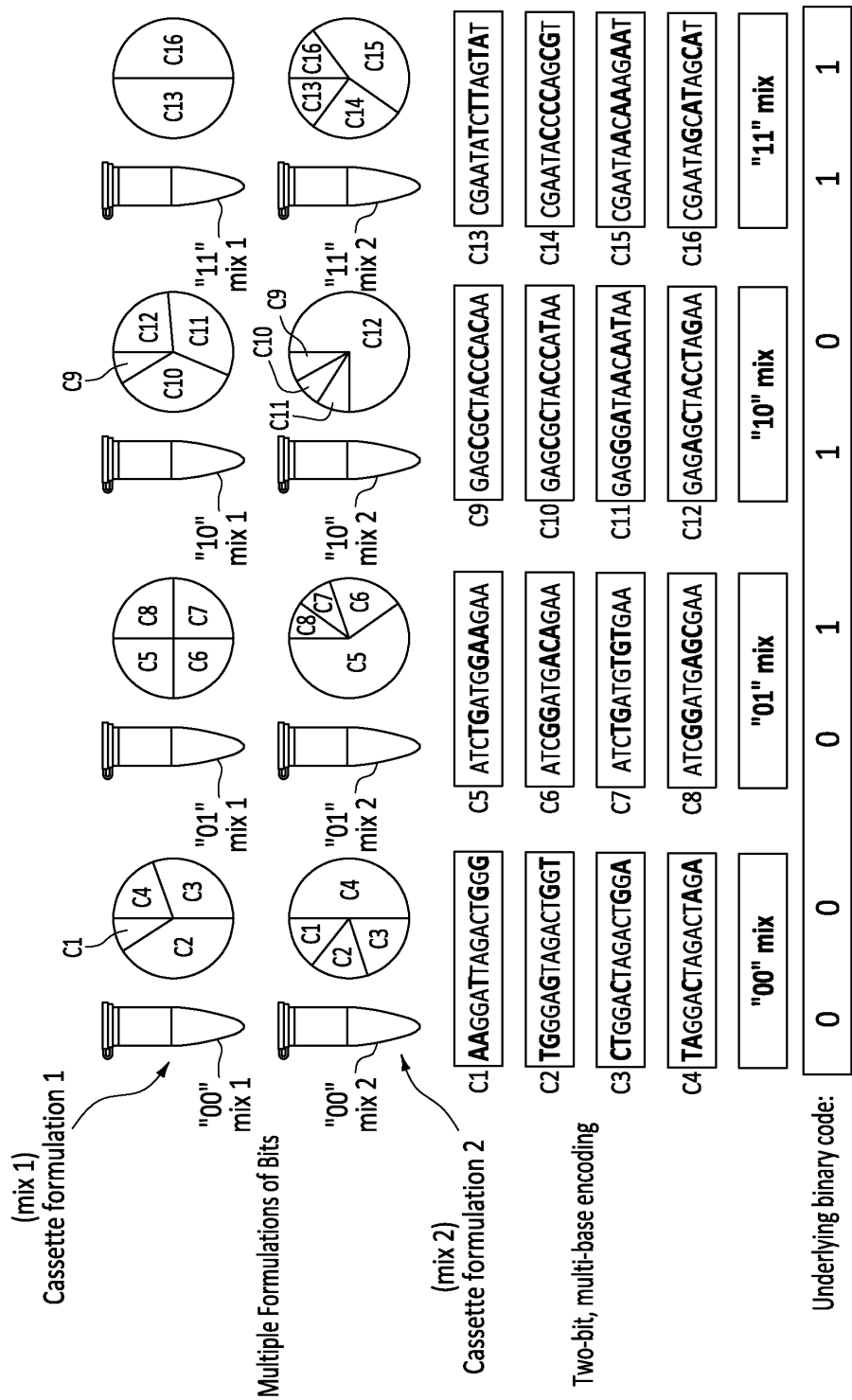


FIG. 5

Heterogeneous Cassette Data Writing

Component	Data	Phase	Cassette(s)
Acceptor	!	_B	DBCO-CTGCT---NNN---TTCTTCC GACGA---NNN---AAGAAGG CCGT
Data	D		GGCA AAGGG TGTC GTA TTCCC ACAG CAT GTGA → 50%
Cassette	E	BA	L _{Topo} GGCA AAGGG TGTC AAT TTCCC ACAG TTA GTGA → 50%
Data	d		CACT AAGGG TGTC CTA GAGT ATTG TTCCC ACAG GAT CTCA TTAAC CCGT → 25%
Cassette	e	AB	L _{Topo} CACT AAGGG TGTC CAA GGT GATA TTCCC ACAG GTT CCA CTAT CCGT → 75%
Data	M		GGCA AAGGG TGTC GGT GATA TTCCC ACAG CCA CTAT GTGA → 25%
Cassette	N	BA	L _{Topo} GGCA AAGGG TGTC GGT GATA TTCCC ACAG CCA CTAT GTGA → 75%
Data	m		CACT AAGGG TGTC CTT AGTG GTTC CTAA → 50%
Cassette	n	AB	L _{Topo} CACT AAGGG TGTC CAT CGTT AATC ATCT → 50%
Cap	#	A_	CACT AAGGGTGTC---NNN---CCGG TTCCCACAG---NNN---GGCC

Homogeneous Cassette Data Writing

Component	Data	Phase	Cassette(s)
Acceptor	!	_B	DBCO-CTGCT---NNN---TTCTTCC GACGA---NNN---AAGAAGG CCGT
Data	D	BA	GGCA AAGGG TGTC GTA TTCCC ACAG CAT GTGA
Cassette	d	AB	L _{Topo} CACT AAGGG TGTC AAT TTCCC ACAG TTA CCGT
Data	M	BA	GGCA AAGGG TGTC GGT GATA TTCCC ACAG CCA CTAT GTGA
Cassette	m	AB	L _{Topo} CACT AAGGG TGTC GTG TTAT TTCCC ACAG CAC AATA CCGT
Cap	#	A_	CACT AAGGGTGTC---NNN---CCGG TTCCCACAG---NNN---GGCC

- NOTES:
- The **bottom strand** will be the resulting sequence after amplification.
 - Topo is bound to the T on the bottom strand
 - Convention is writing LEFT to RIGHT
 - The top symbol is used in writing, all symbols are used in reading

FIG. 6

Writing 0110111 to a single nucleic acid data packet (nacket) - I

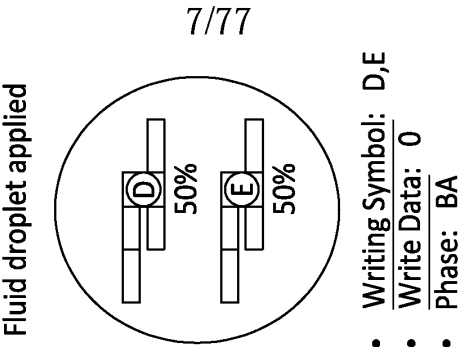
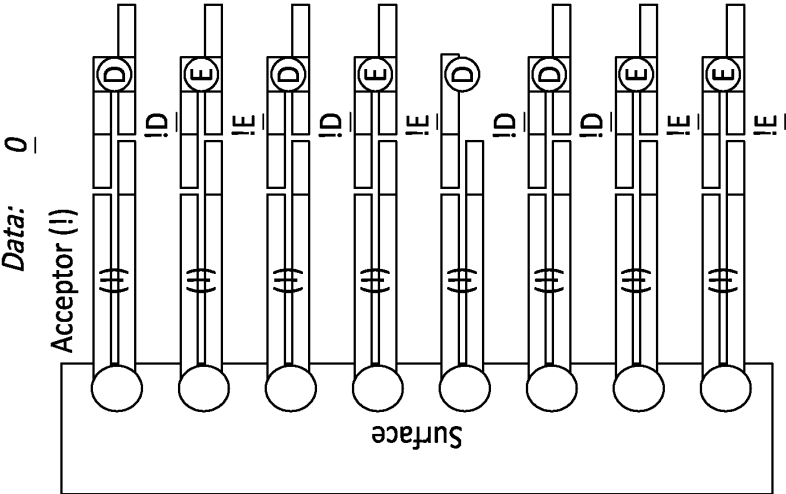


FIG. 7

Writing 011011 to a single nacket - II

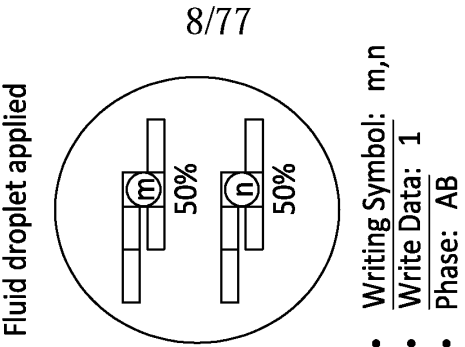
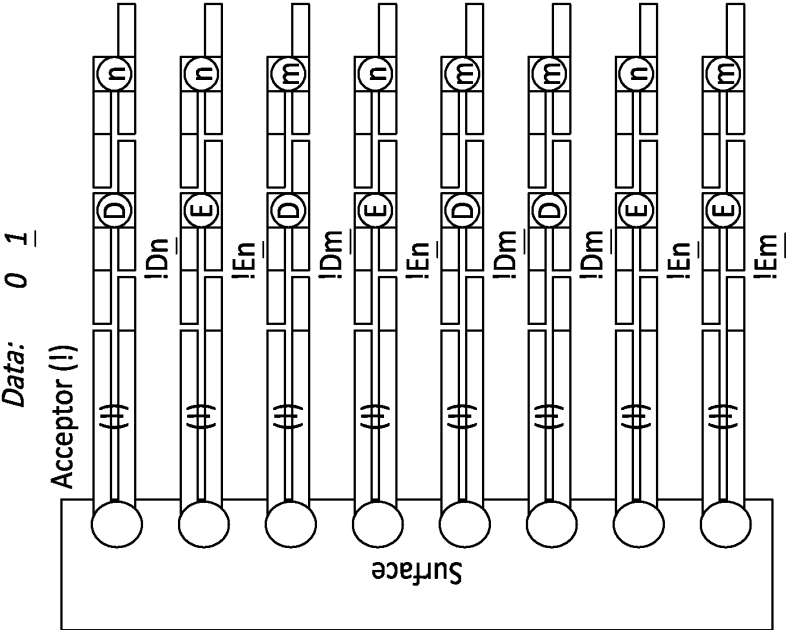


FIG. 8

Writing 011011 to a single nacket - III

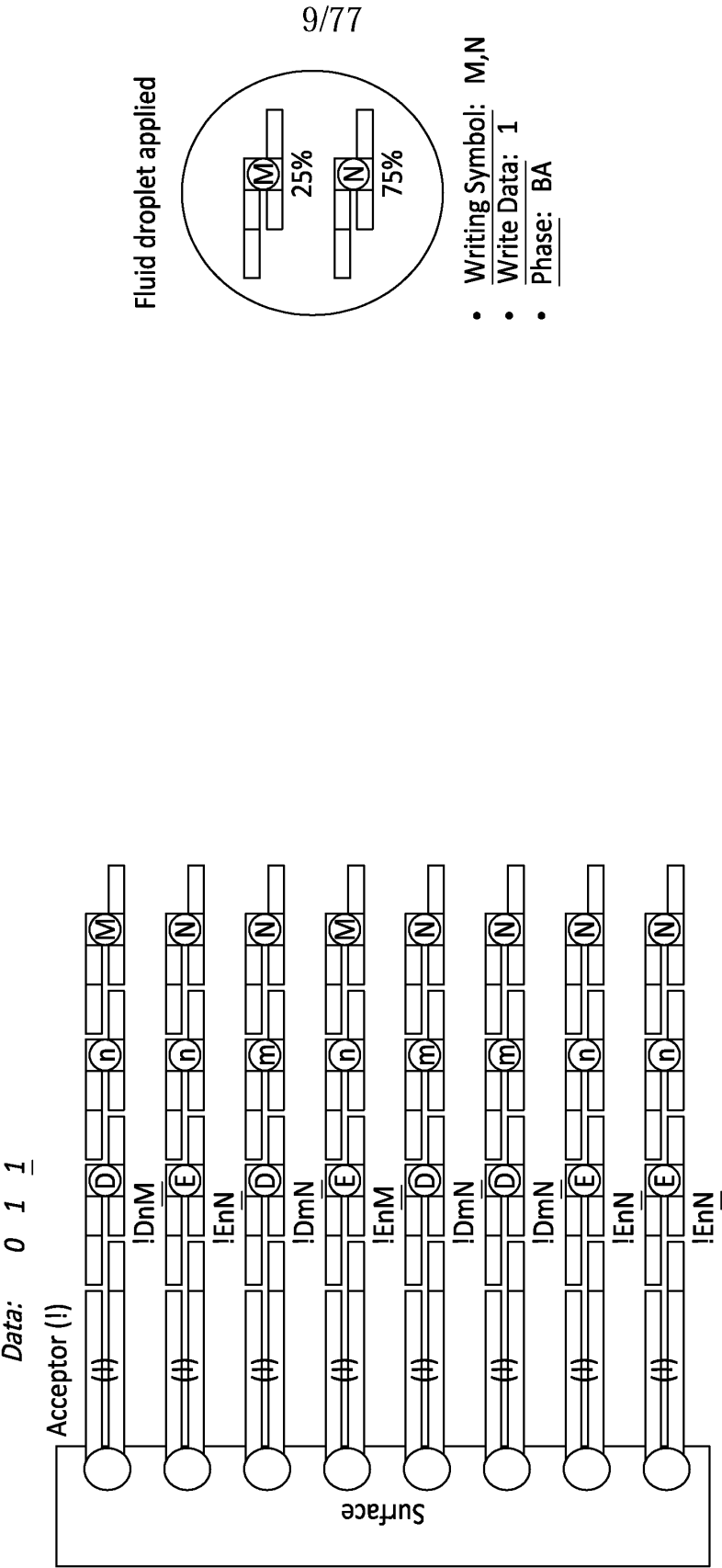
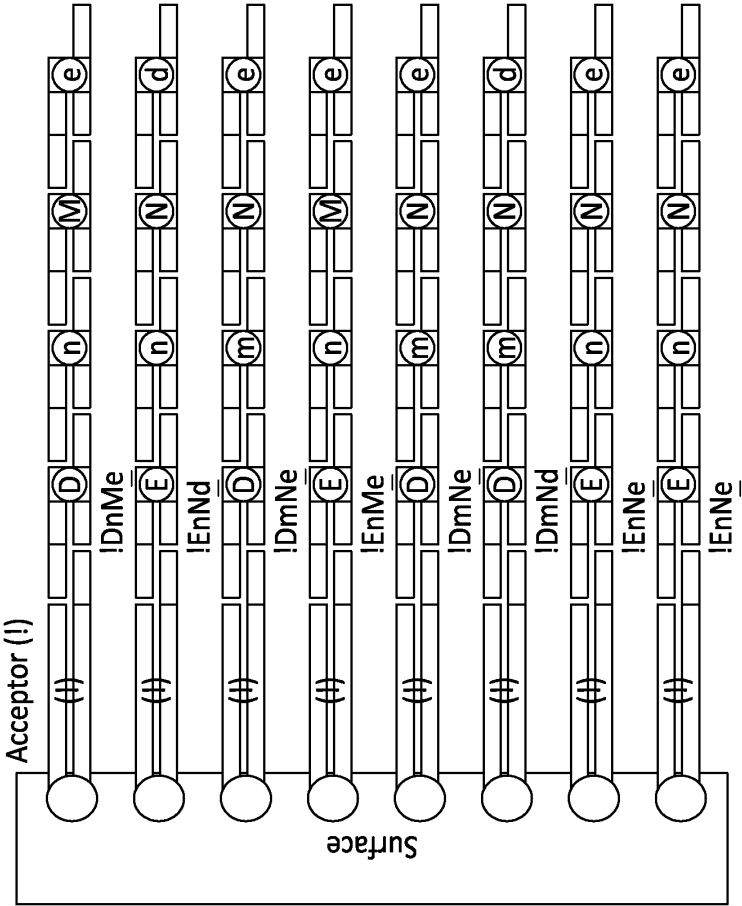


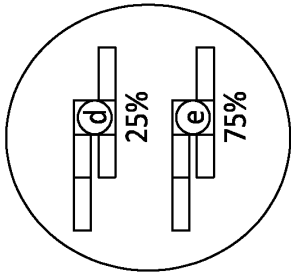
FIG. 9

Writing 011011 to a single nacket - IV

Data: 0 1 1 1 0



Fluid droplet applied



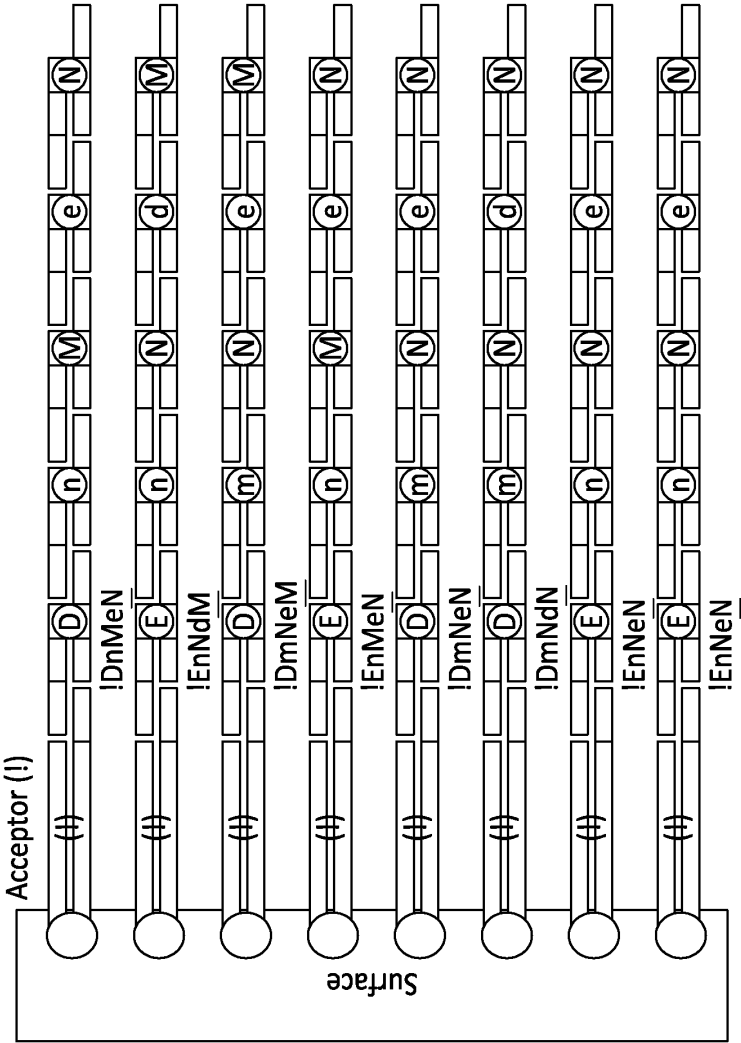
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- Writing Symbol: d,e
- Write Data: 0
- Phase: AB

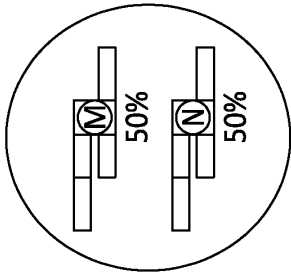
FIG. 10

Writing 011011 to a single nacket - V

Data: 0 1 1 0 1 1



Fluid droplet applied



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- Writing Symbol: M,N
- Write Data: 1
- Phase: BA

FIG. 11

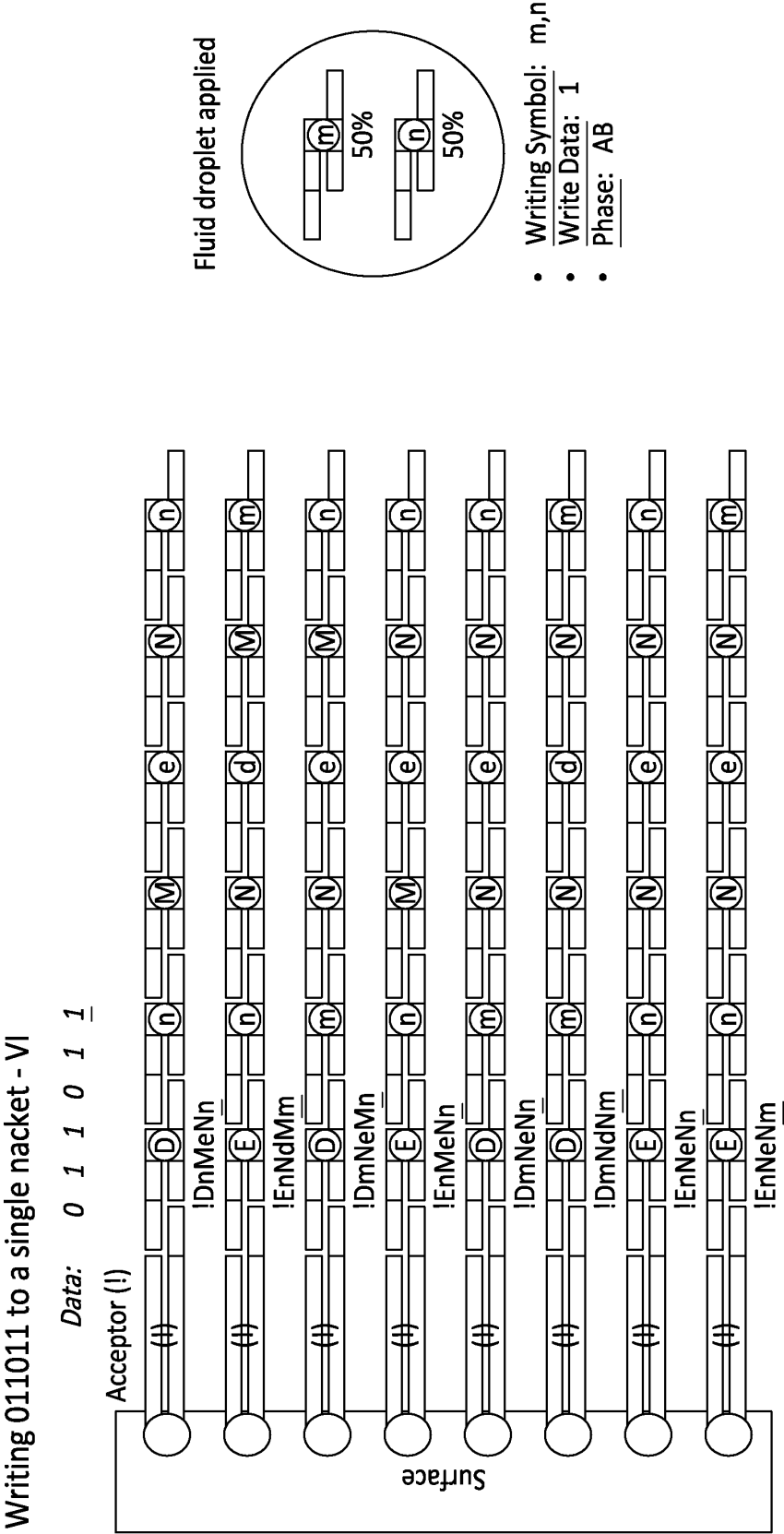
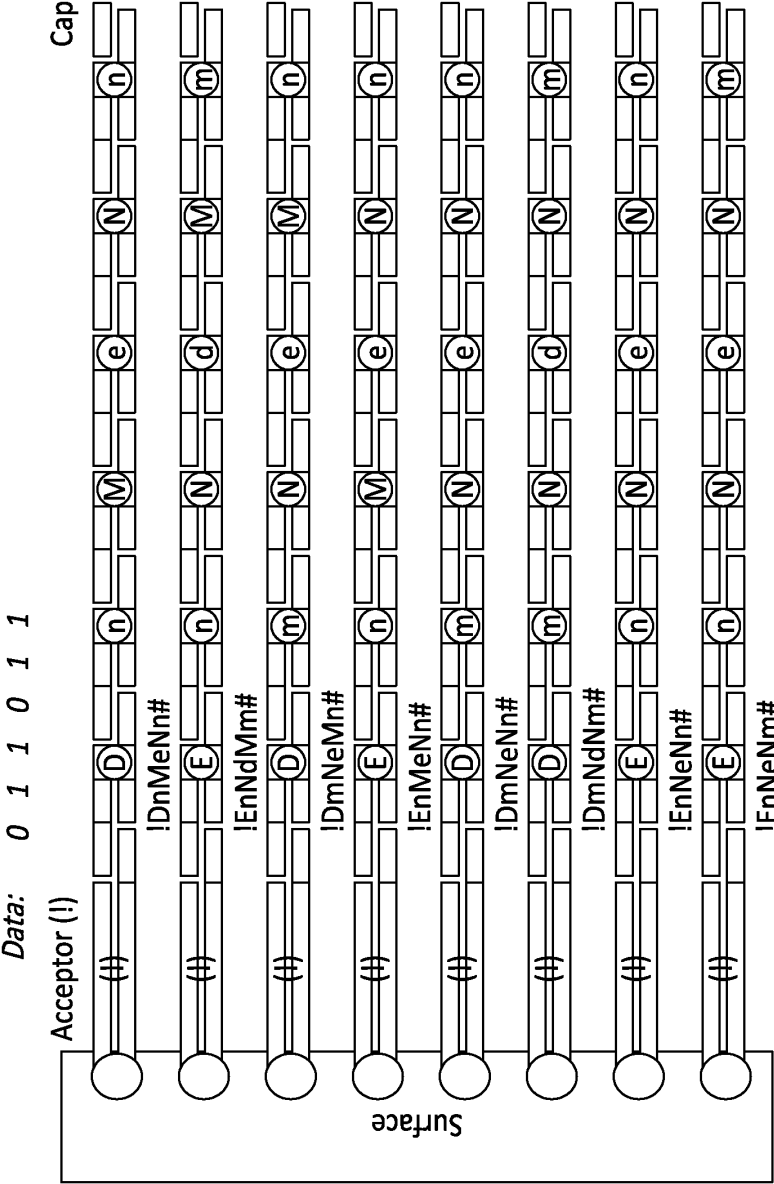
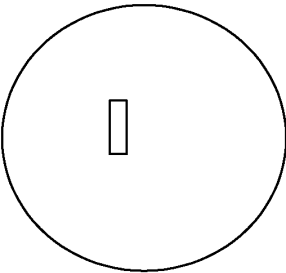


FIG. 12

Writing 011011 to a single nacket - VII (cap)



Fluid droplet applied



- Writing Symbol: #
- Phase: A_

FIG. 13

Write a 32-byte NFT hash in DNA - challenges for single base synthesis
32bytes X 8 bits/byte = 256 bits / 2 bits per DNA block = 128 DNA blocks.

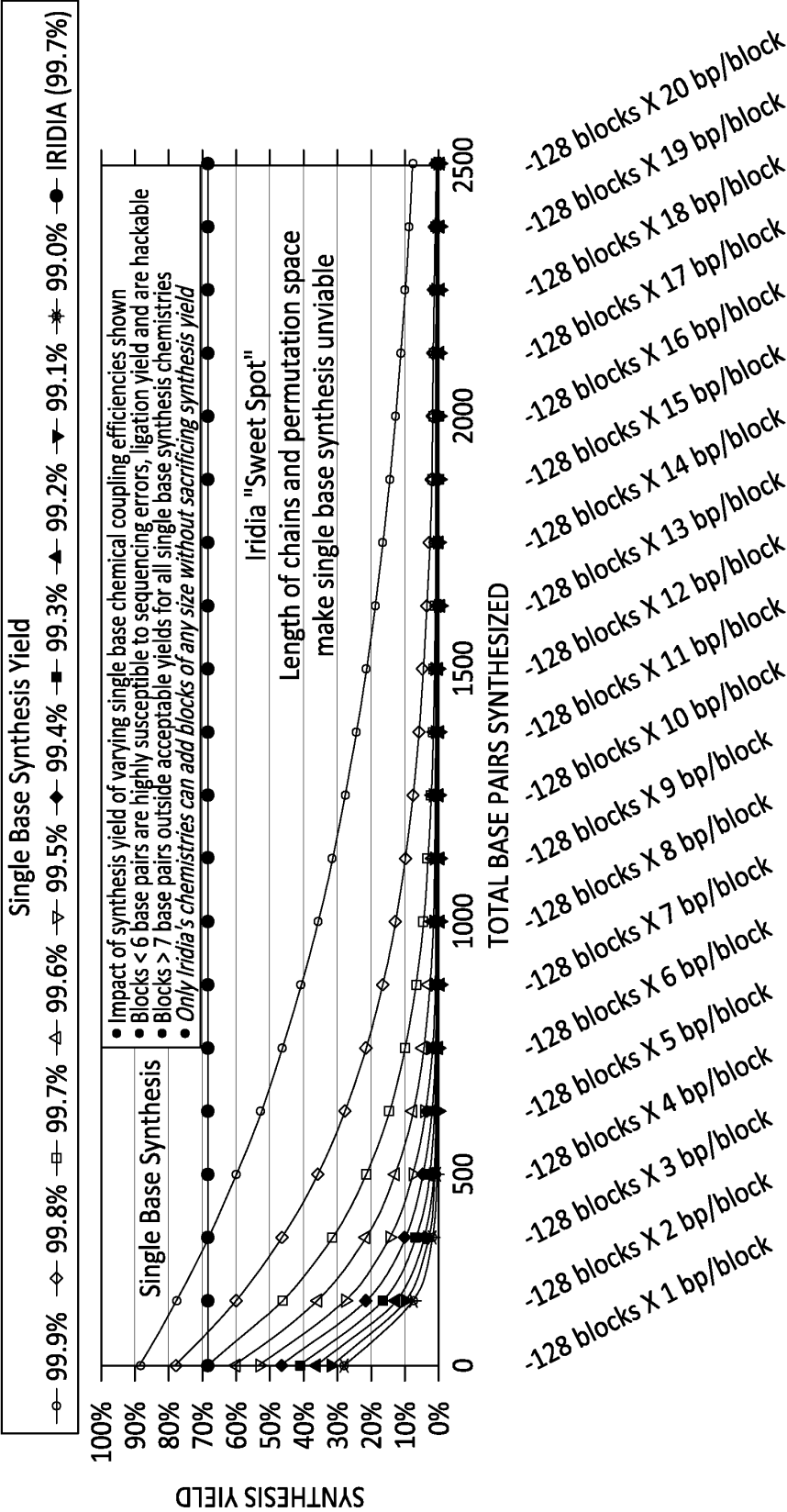


FIG. 14

Write a 32-byte NFT into 16, 12-cassette chains
Synthesize with existing laboratory robotic systems. Read with an Illumina iSeq100

I. NFT:	NFT minimum data size	32 bytes	A00B	0		A B C D E F G H I J 0 1 2 3 4 5 6 7 8 9
II. Cassette Chemistry	Bit Depth:	2	A01B	1		Q R S T U V W X Y Z 0 1 2 3 4 5 6 7 8 9
	Number of cassettes per fluid, N	10				
	Average length of cassette, L_cassette	17 bases				
	Cap, C	29 bases	B00A	0		a b c d e f g h i j 0 1 2 3 4 5 6 7 8 9
	Acceptor, A	29 bases				
	Total Length, L	262 = C + A + N * L_cassette	B01A	1		q r s t u v w x y z 0 1 2 3 4 5 6 7 8 9
III. Encoding Scheme	Address	4 bits	A10B	2		A B X Δ E Φ Γ H I ϑ 0 1 2 3 4 5 6 7 8 9
	Writing Length	12 cassettes				
	# of nackets in sector	16 bits				
	CRC length	4 bits	A11B	3		⊕ P Σ T Y ζ Ω Ξ Ψ Z 0 1 2 3 4 5 6 7 8 9
	Total length	24 bits per chain				
	Payload per chain	16 bits per chain				
	Sector size	256 bits per sector	B10A	2		α β χ δ ε φ γ η ι ϕ 0 1 2 3 4 5 6 7 8 9
	Random number combinations	32 bits per sector				
		1.6E+13 bit random numbers	B11A	3		θ ρ σ τ υ ω ξ ψ ζ 0 1 2 3 4 5 6 7 8 9
IV. Illumina Sequencing Design	Read length, each side	151 bases				
	Overlap	40 bases				
	Max read length	262 bases				

FIG. 15

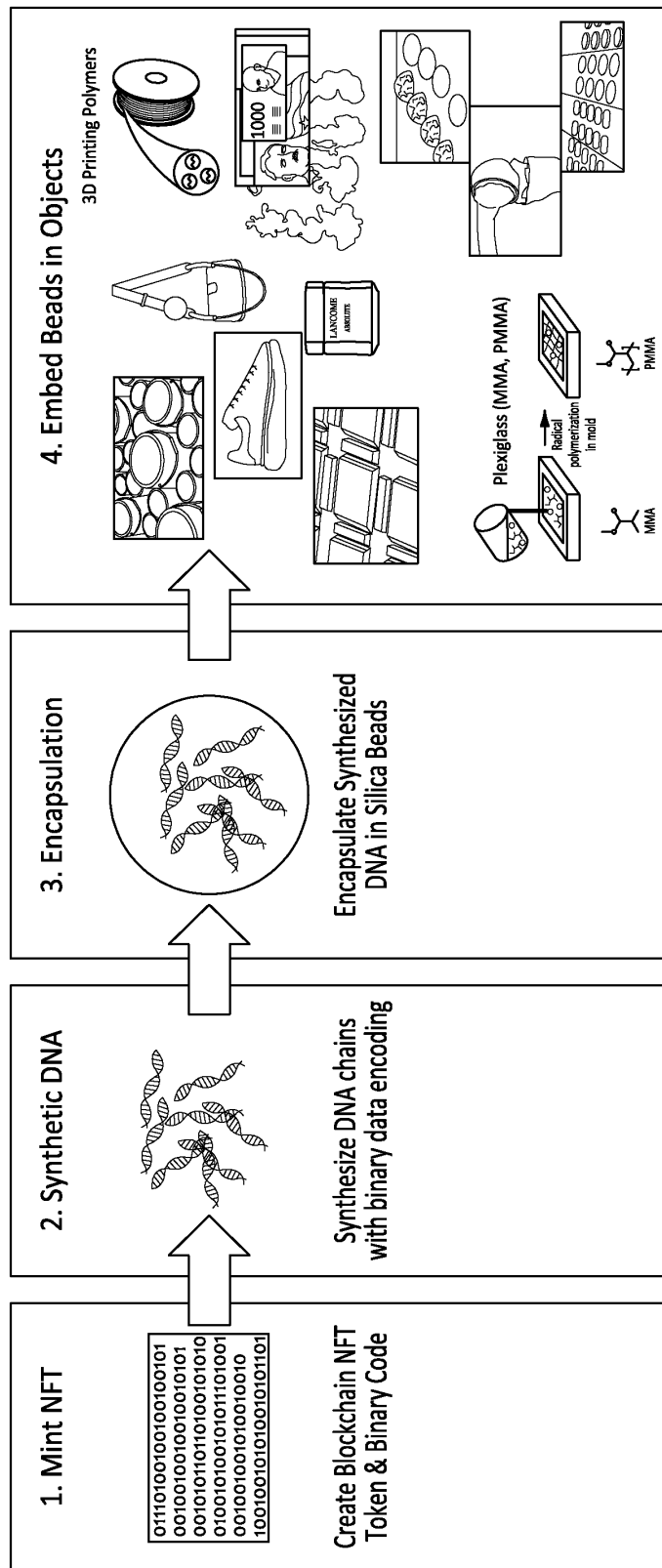


FIG. 16

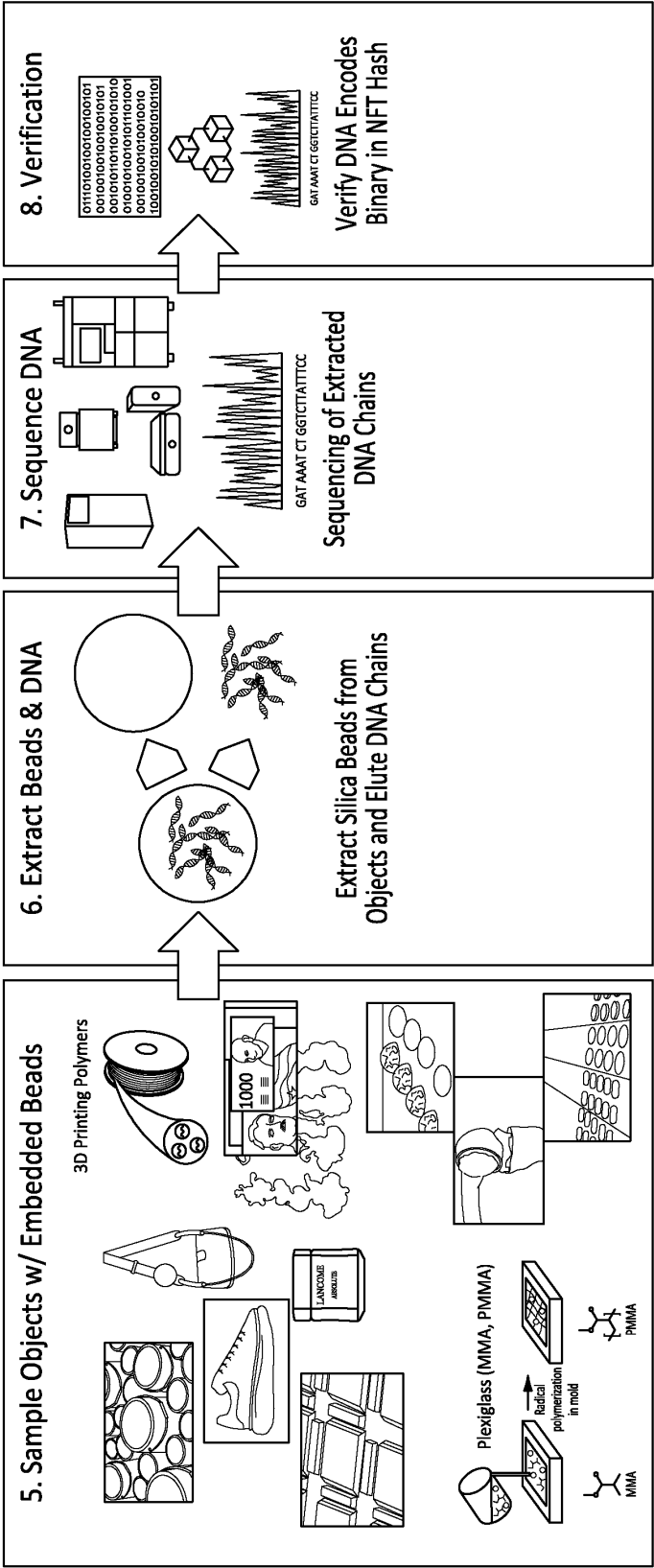


FIG. 17

Object Identification & Origin

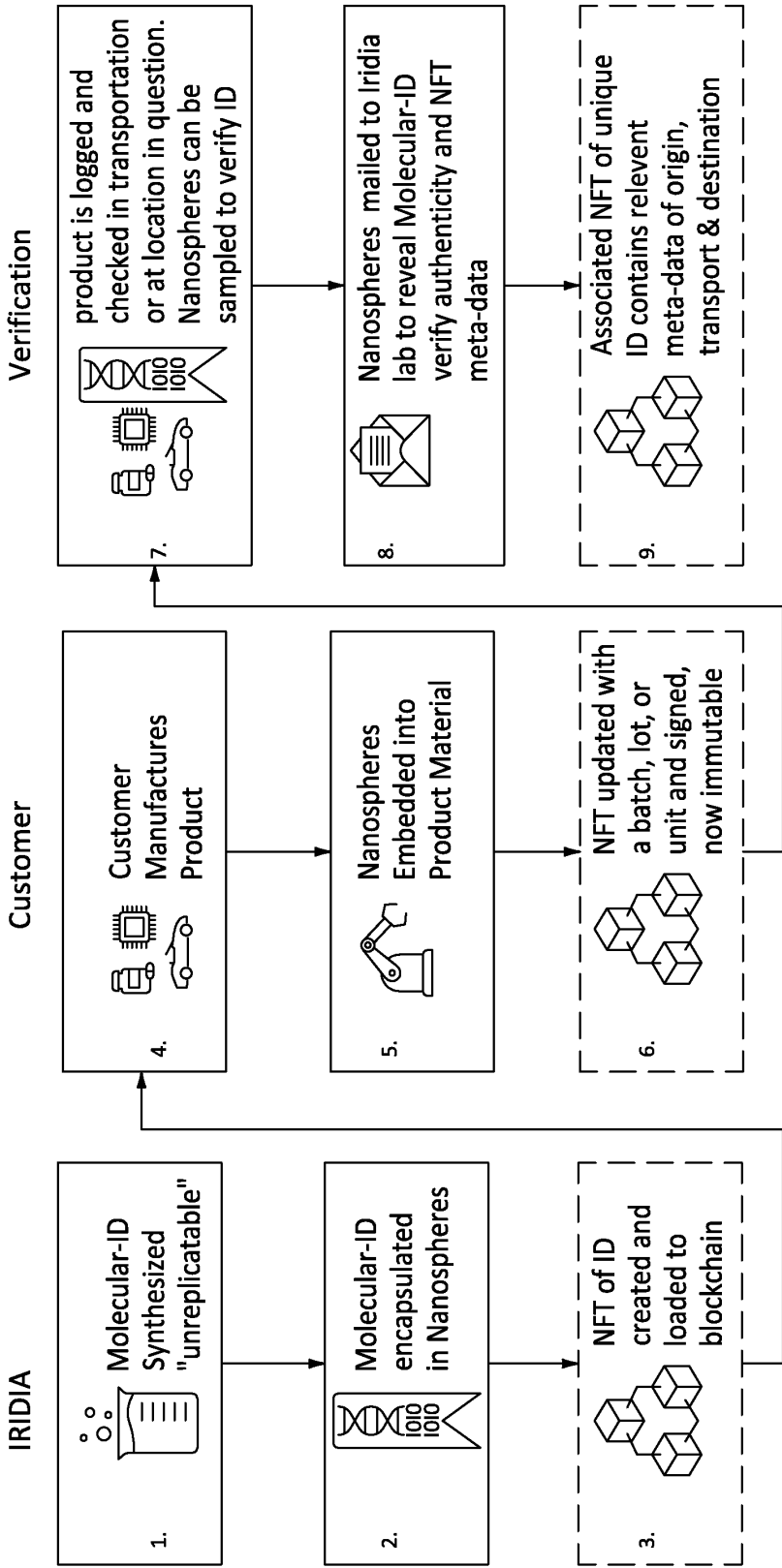


FIG. 18

Topoisomerase ("Topo") cassettes can be highly variable

Cassettes can be of varying length and composition & be used to encode many possible combinations of bits

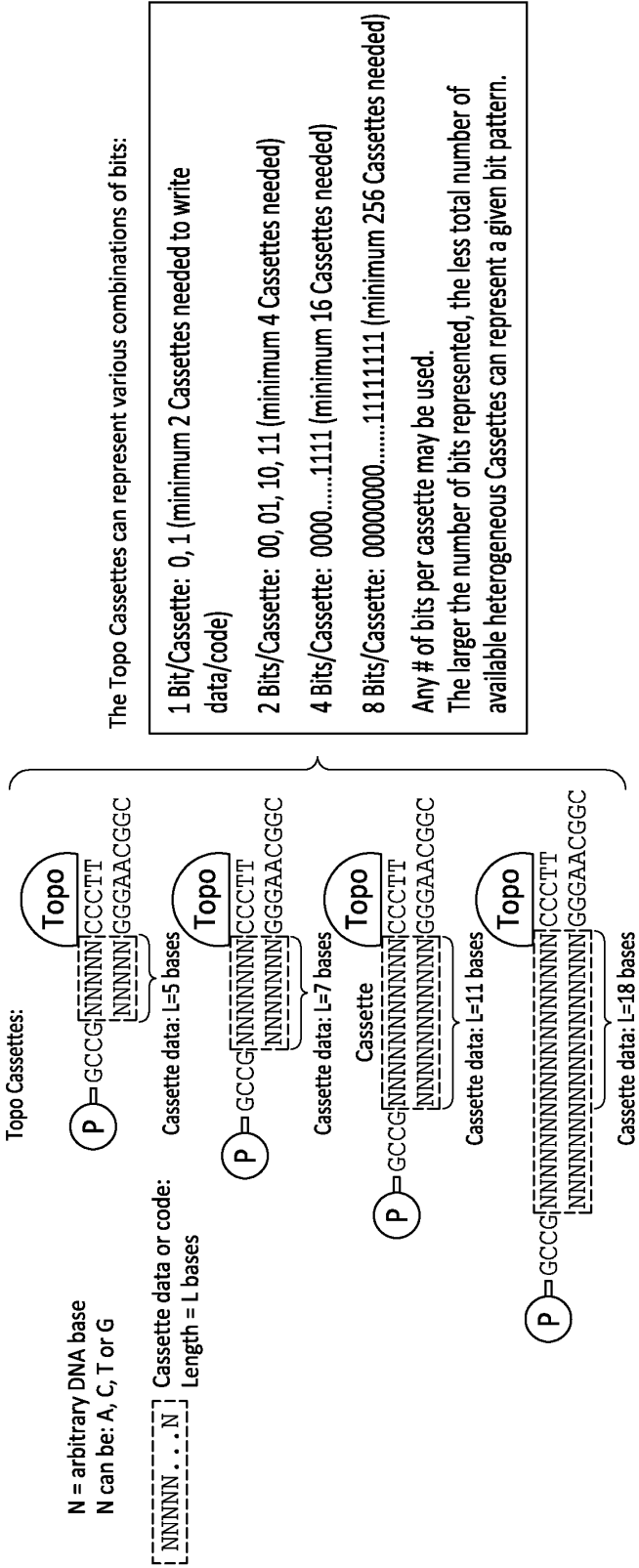
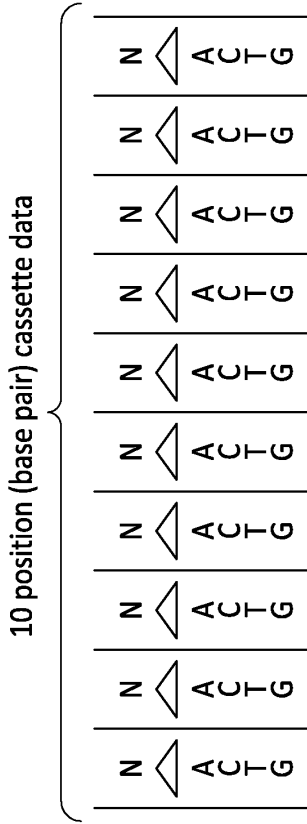


FIG. 19

Depending on Topo cassette data size (# of positions), many unique cassettes are possible



Depending on cassette size (# of positions), many unique cassettes are possible for representing any set of binary bits (1, 2, 4, 8, etc.)

20 base pairs	NNNNNNNNNNNNNNNNNNNNNN	$4^{20} = 1,099,511,627,776$	potential cassettes to represent 1, 2, 4, or 8-bit combinations
19 base pairs	NNNNNNNNNNNNNNNNNNNNN	$4^{19} = 274,877,906,944$	potential cassettes to represent 1, 2, 4, or 8-bit combinations
18 base pairs	NNNNNNNNNNNNNNNNNNNN	$4^{18} = 68,719,476,736$	potential cassettes to represent 1, 2, 4, or 8-bit combinations
17 base pairs	NNNNNNNNNNNNNNNNNNN	$4^{17} = 17,179,869,184$	potential cassettes to represent 1, 2, 4, or 8-bit combinations
16 base pairs	NNNNNNNNNNNNNNNNNN	$4^{16} = 4,294,967,296$	potential cassettes to represent 1, 2, 4, or 8-bit combinations
15 base pairs	NNNNNNNNNNNNNNNNN	$4^{15} = 1,073,741,824$	potential cassettes to represent 1, 2, 4, or 8-bit combinations

FIG. 20

Create multiple cassettes that specify the same underlying binary information

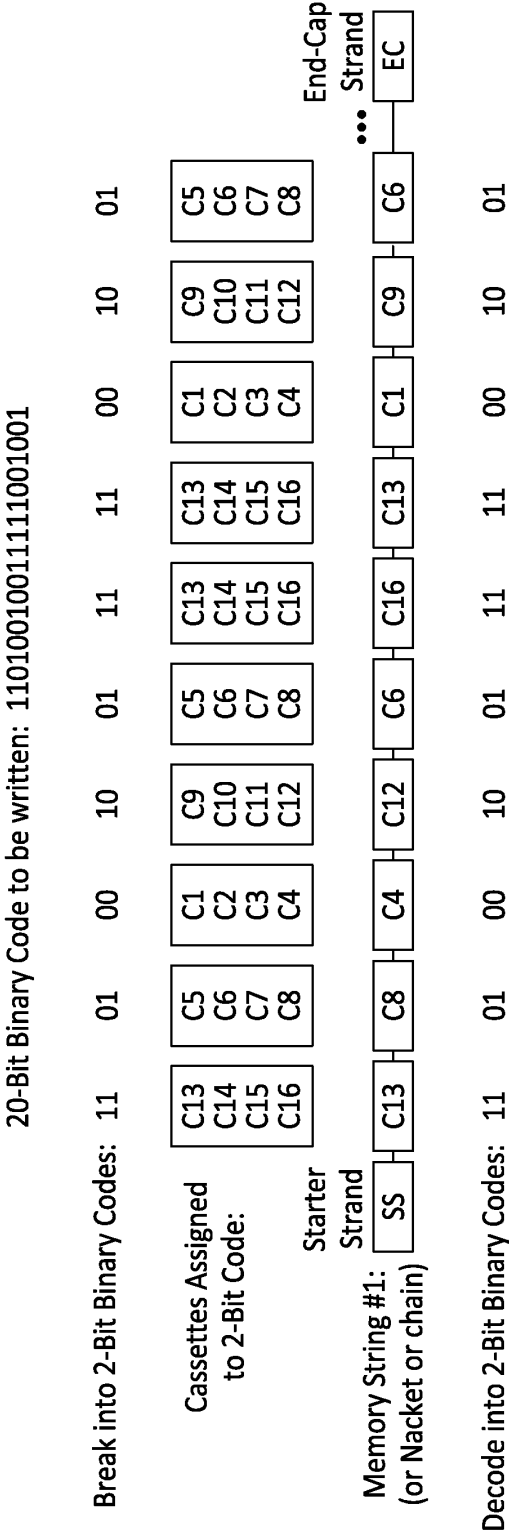
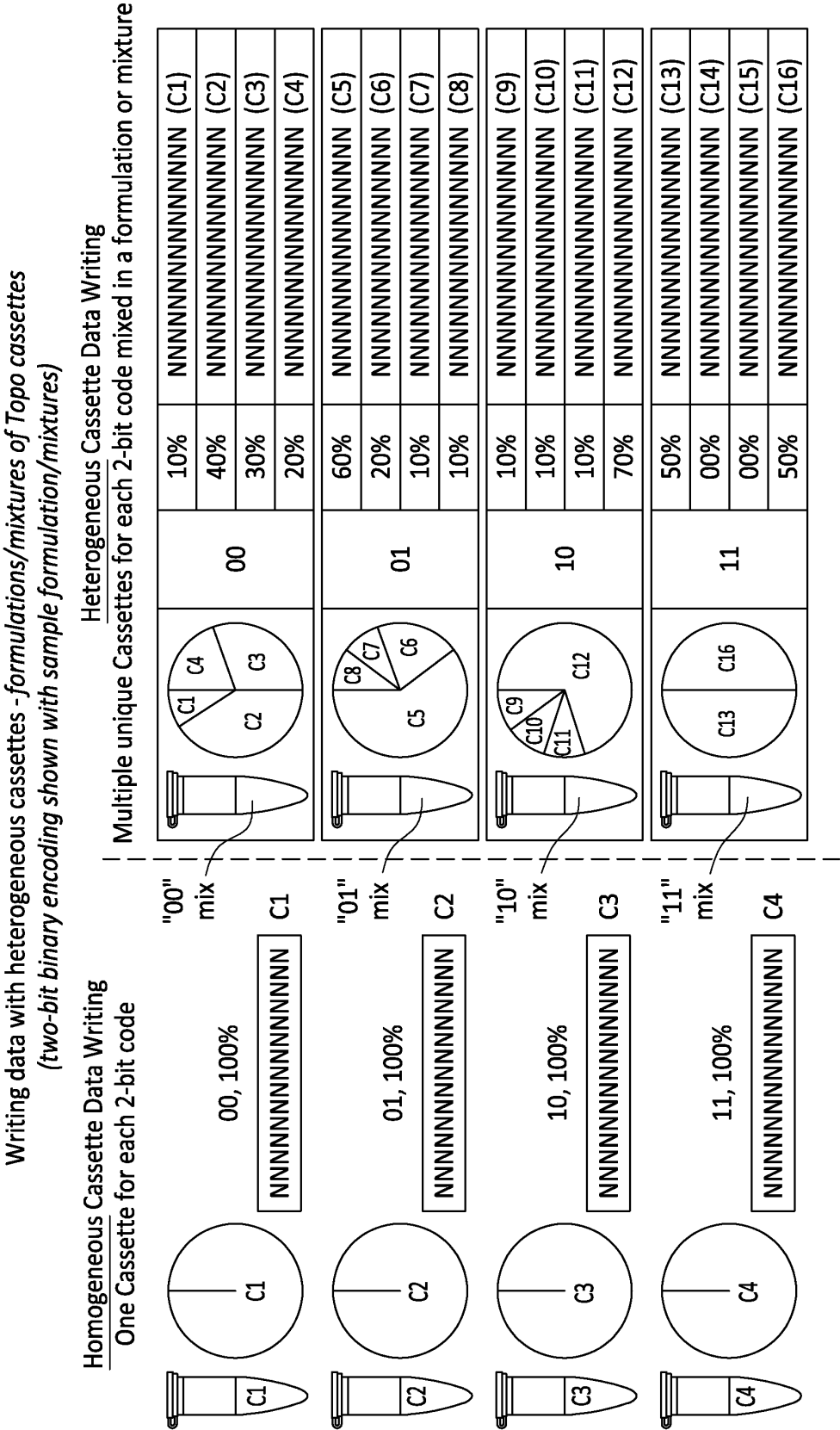


FIG. 21



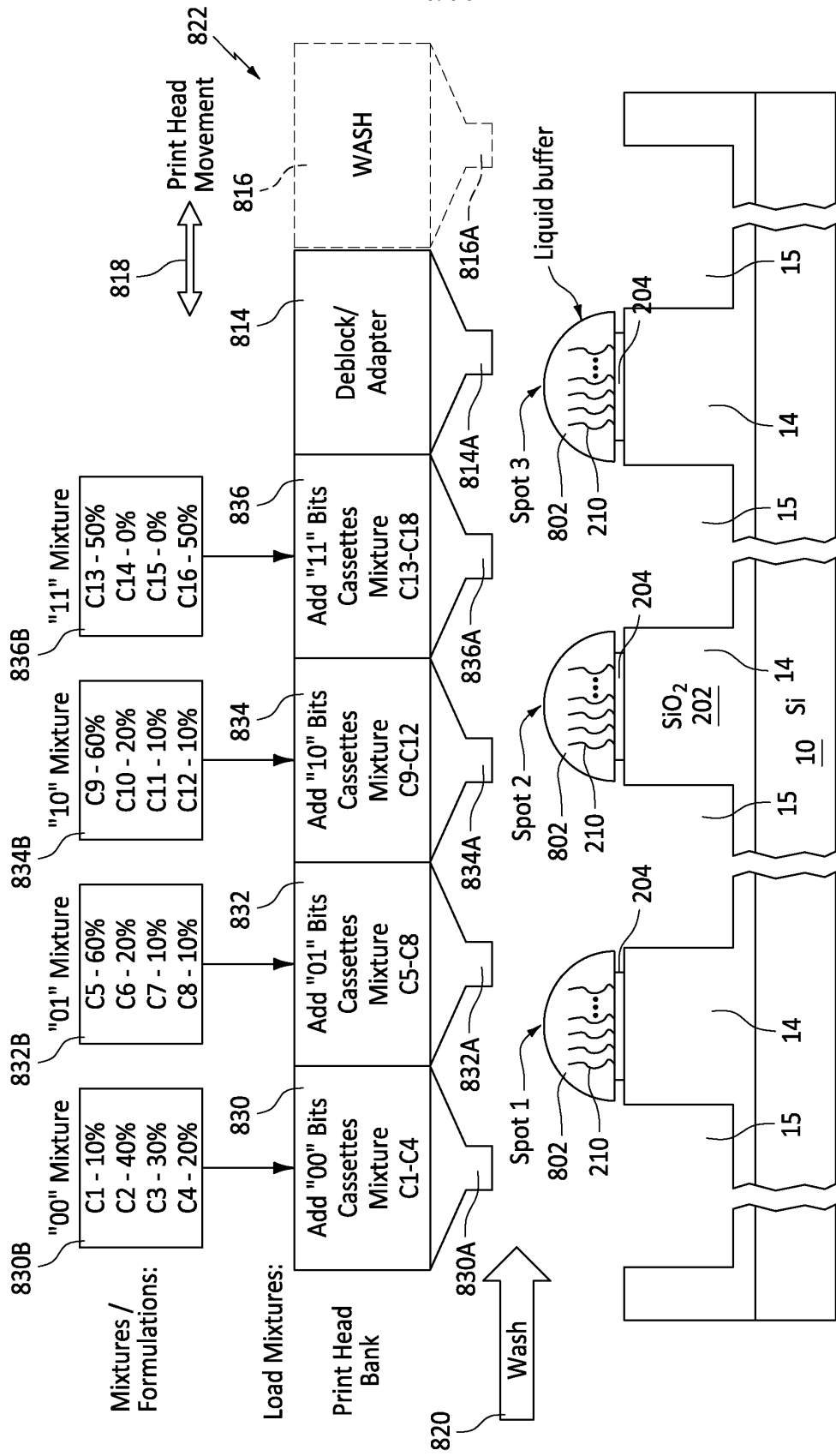


FIG. 23

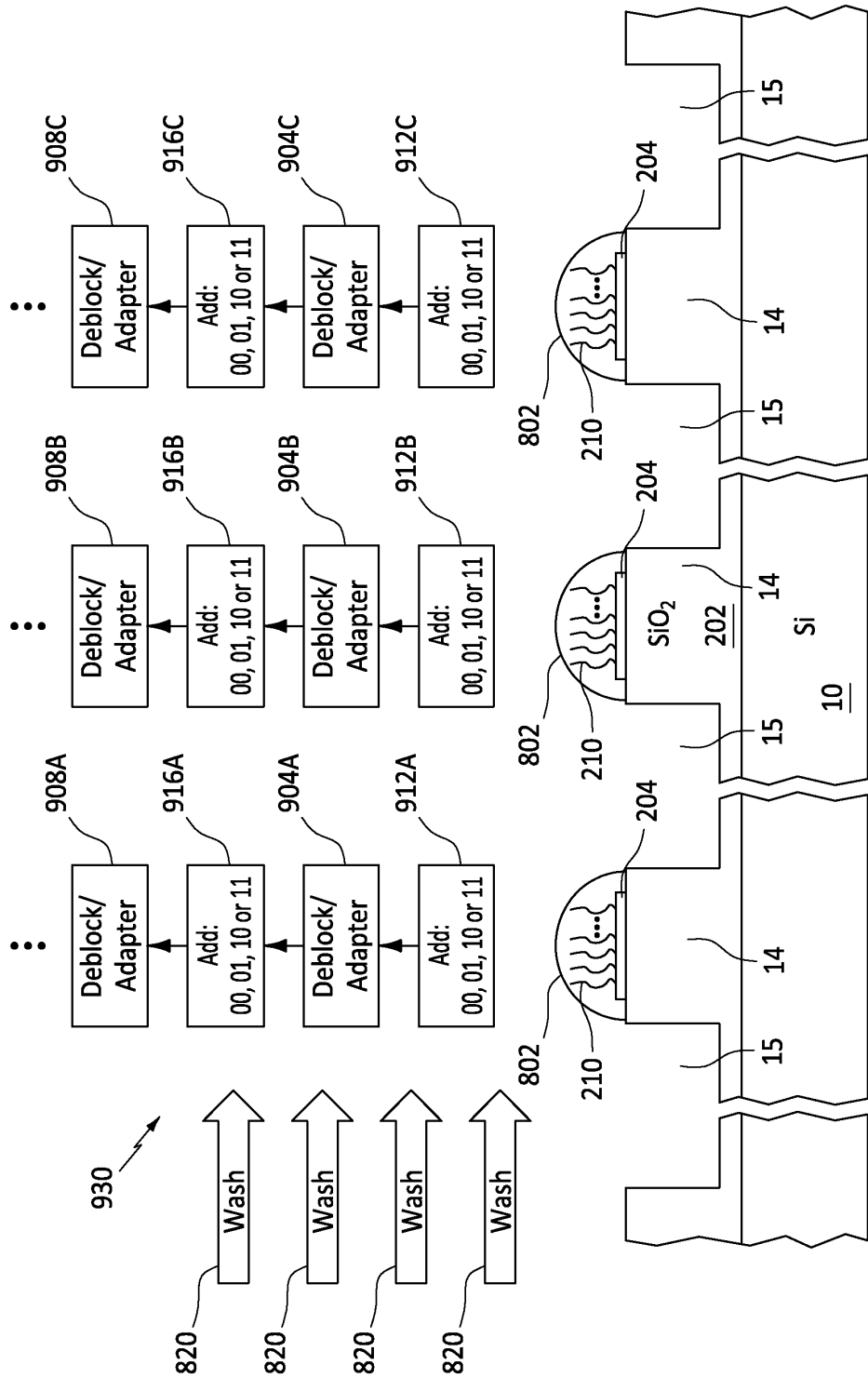


FIG. 24

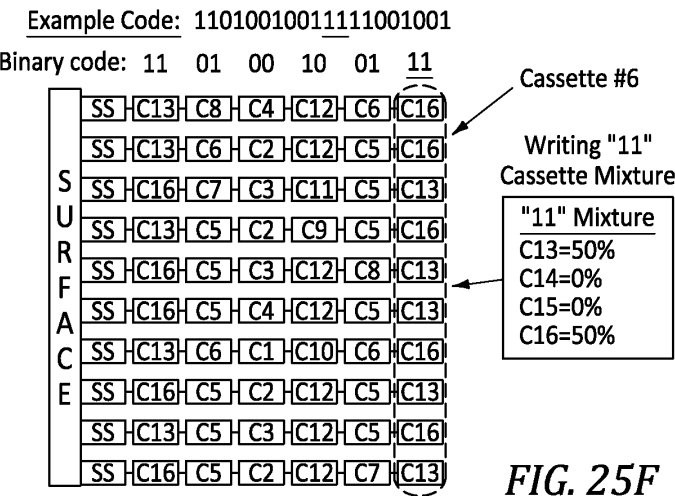


FIG. 25F

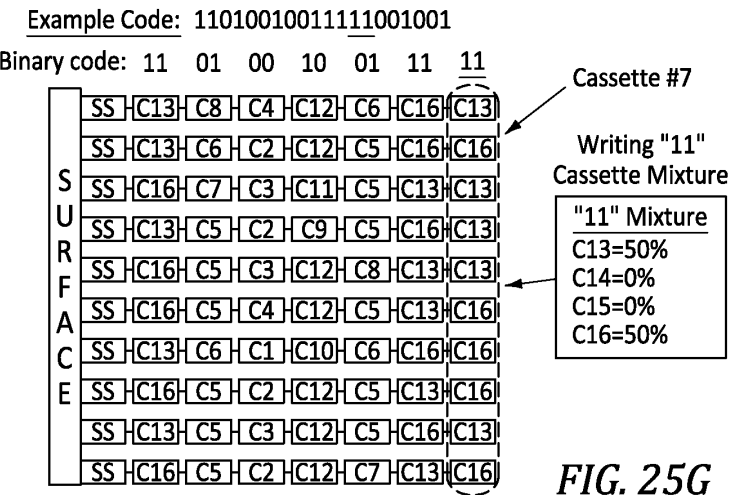


FIG. 25G

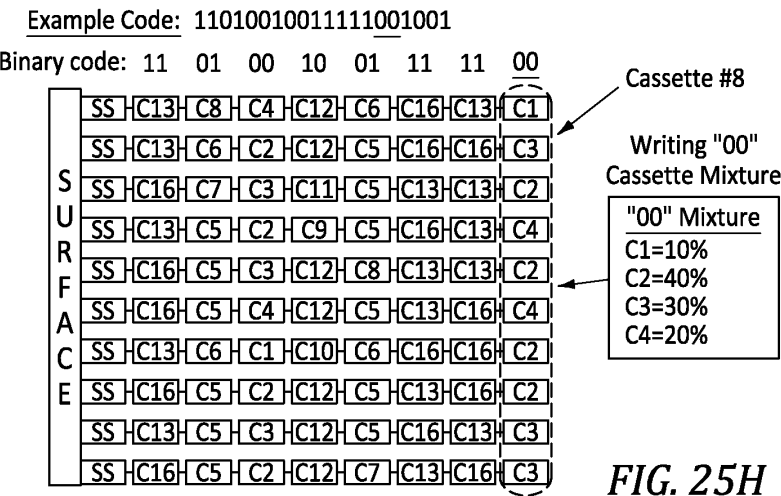


FIG. 25H

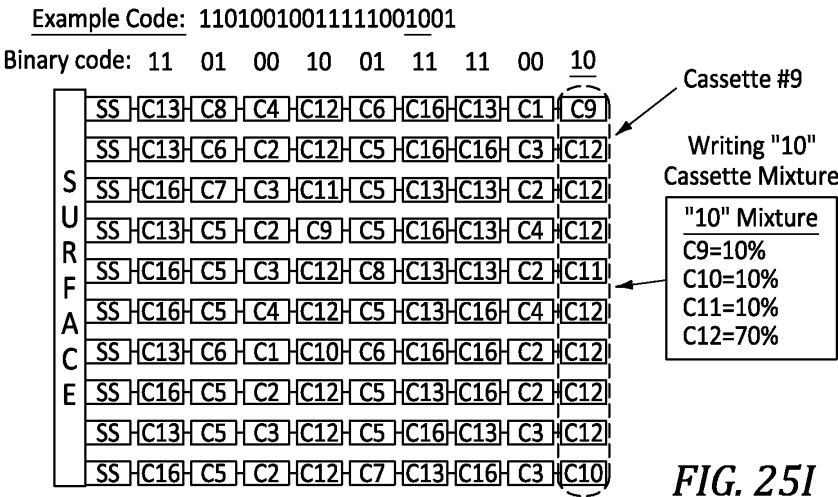


FIG. 25I

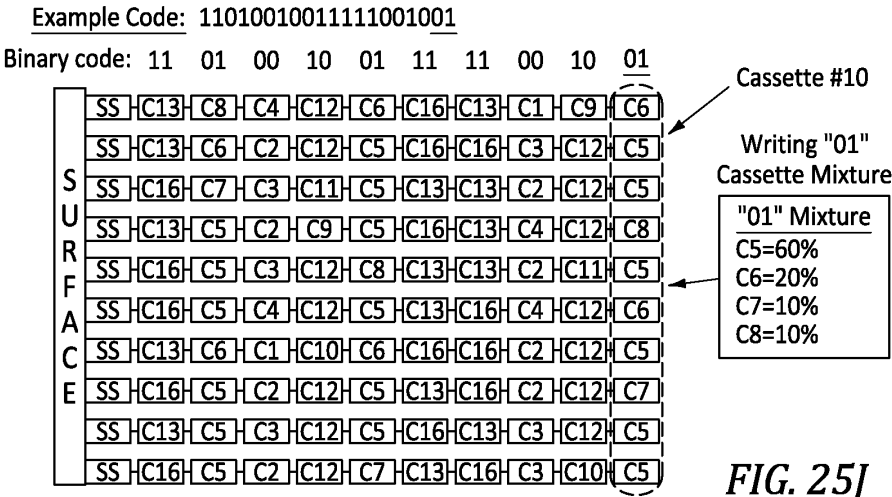


FIG. 25J

Randomness and Validation along Memory String (or Nacket)

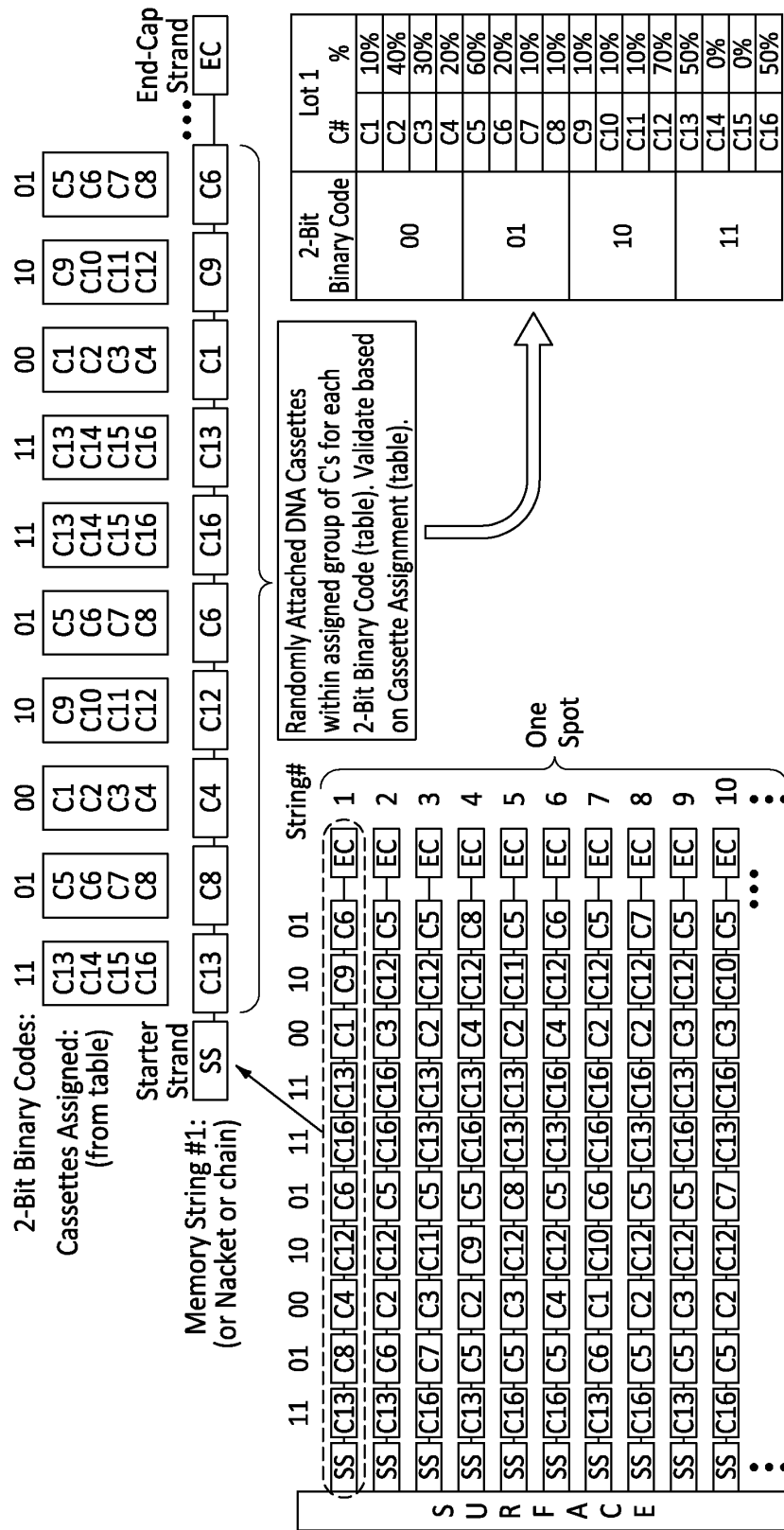


FIG. 26

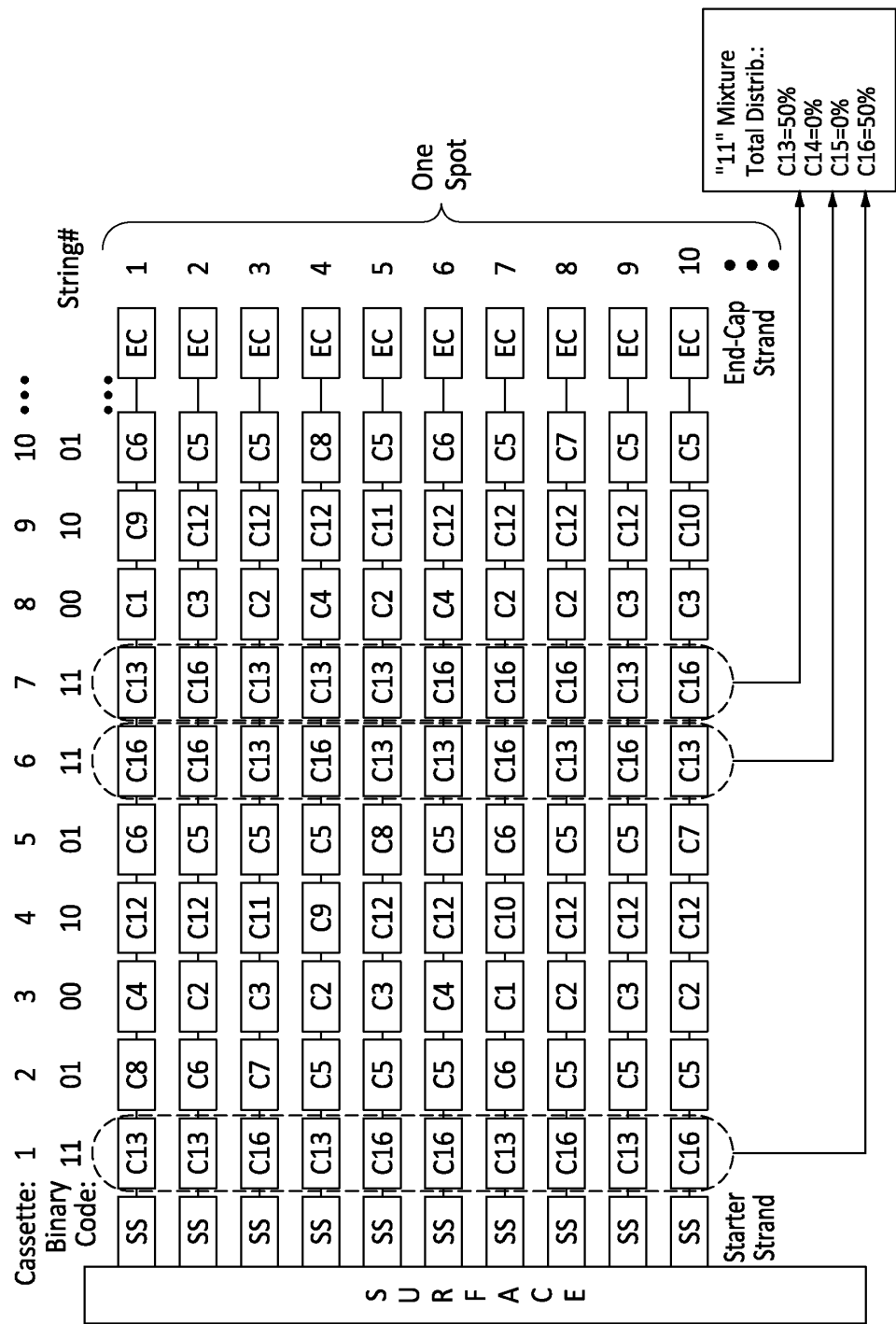


FIG. 27A

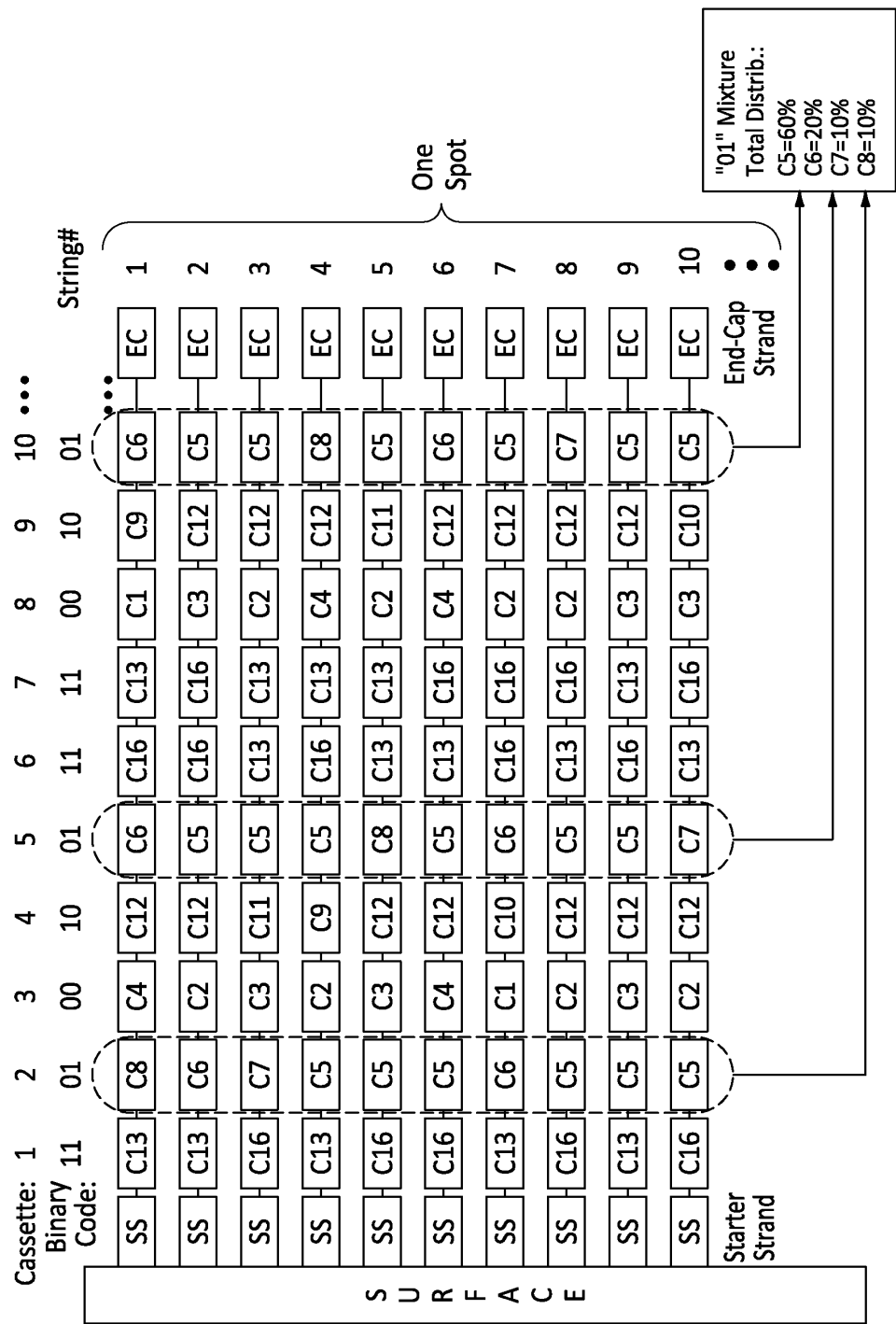


FIG. 27B

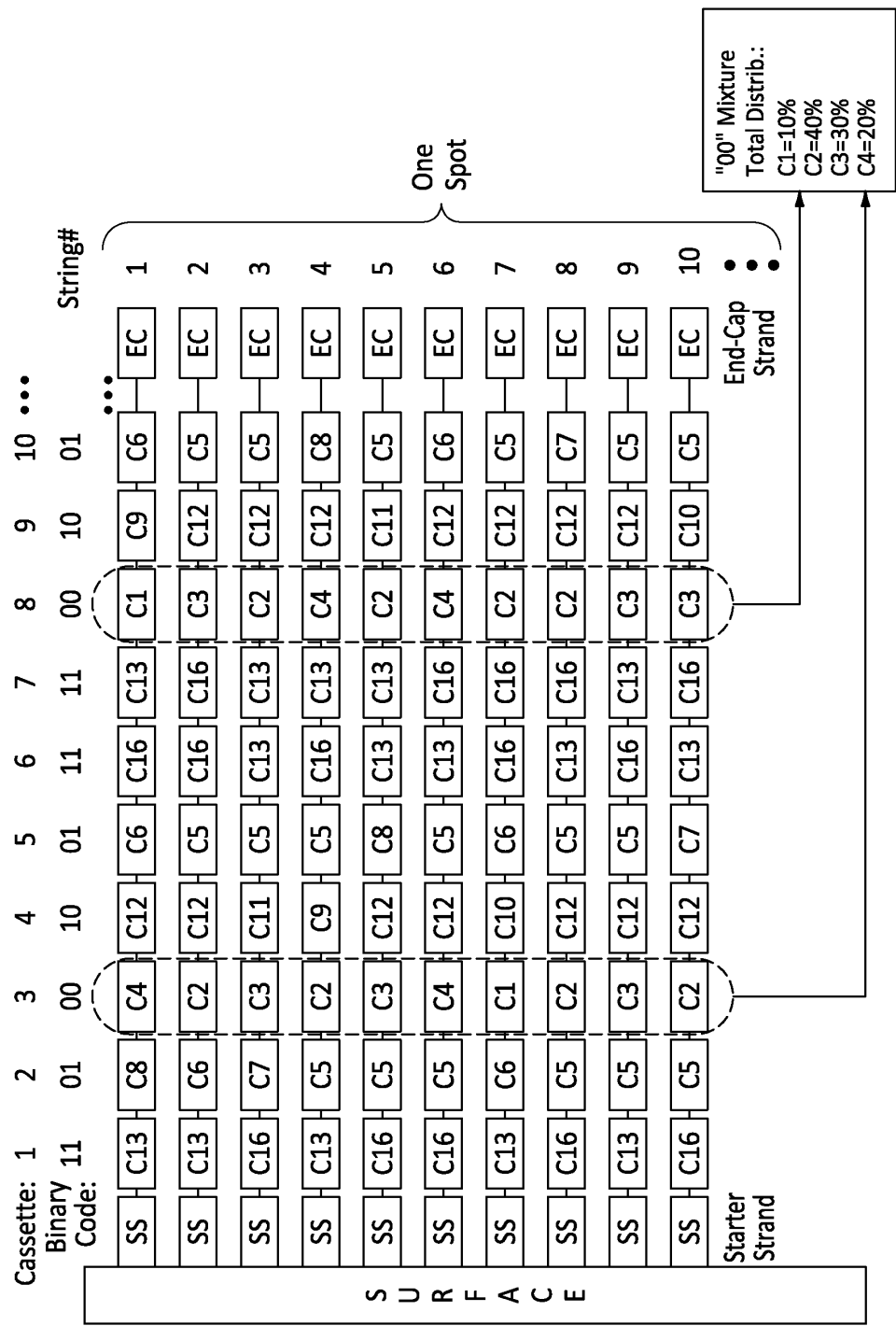


FIG. 27C

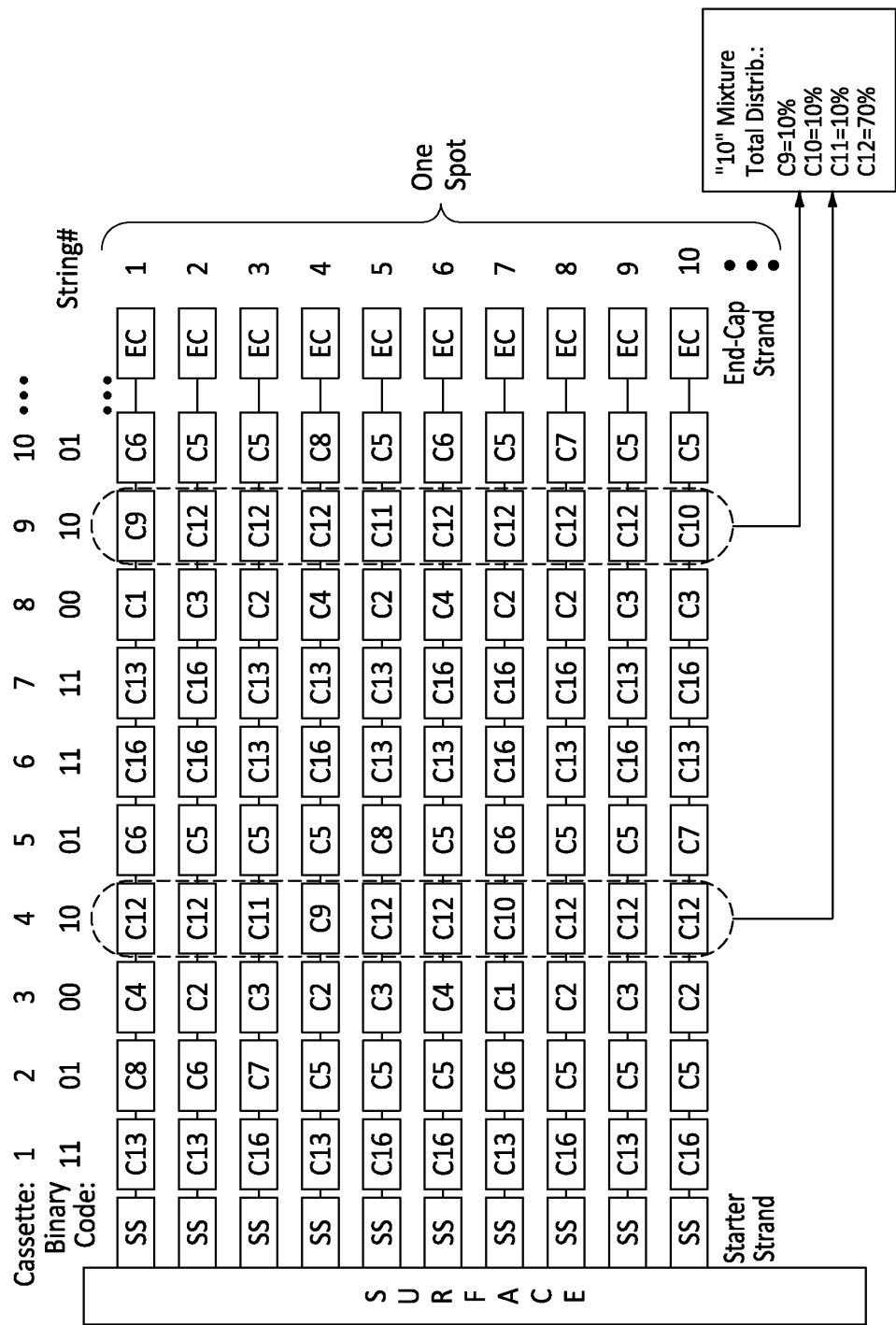


FIG. 27D

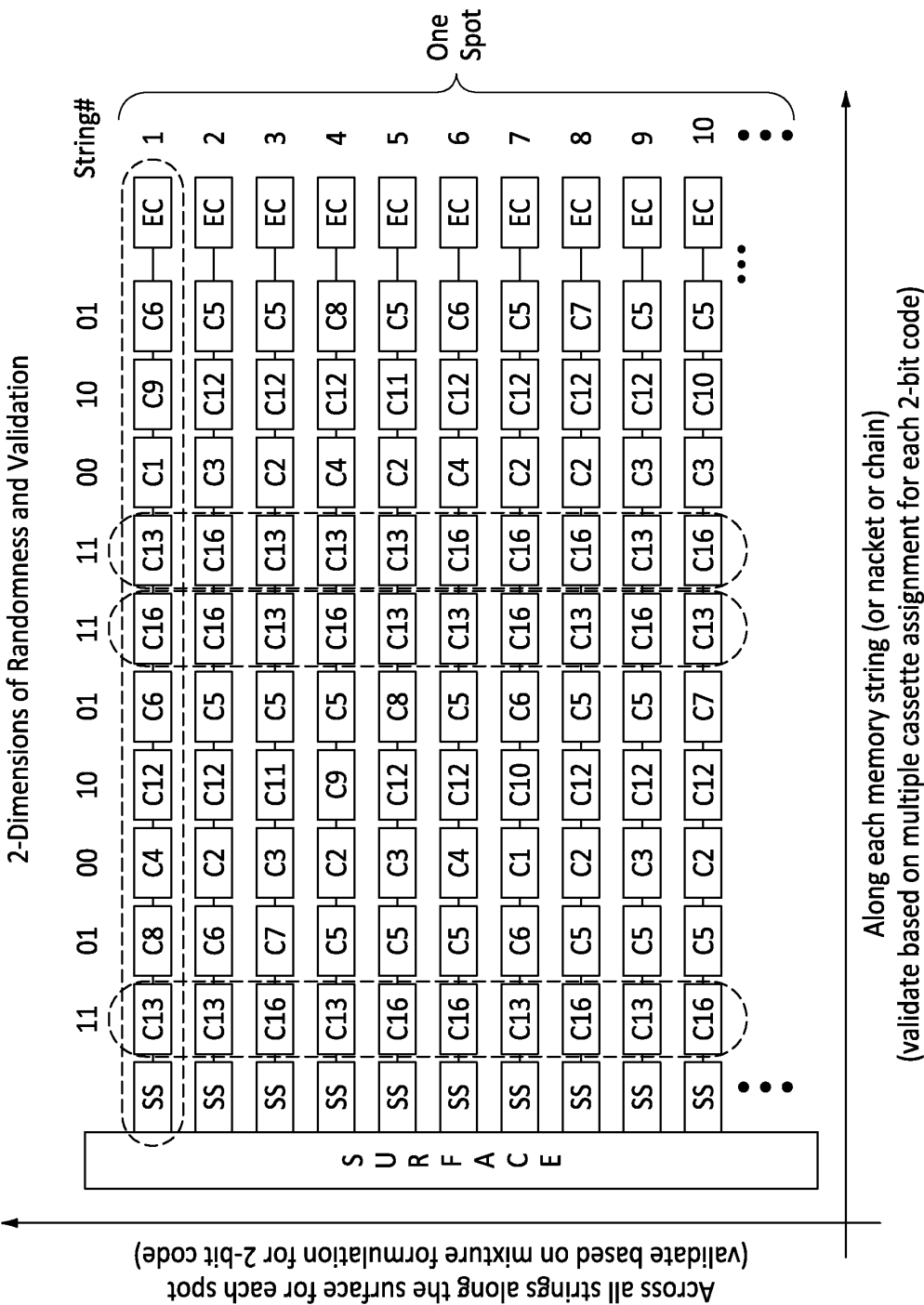


FIG. 28

Binary Code to Cassette Table								
Binary Code	Lot 1		Lot 2		Lot 3		Lot 4	
	C#	%	C#	%	C#	%	C#	%
00	C1	10%	C16	20%	C1	30%	C13	10%
	C2	40%	C1	30%	C5	20%	C14	20%
	C3	30%	C2	40%	C9	10%	C15	40%
	C4	20%	C3	10%	C13	40%	C16	30%
01	C5	60%	C4	20%	C2	10%	C1	10%
	C6	20%	C5	10%	C6	60%	C2	10%
	C7	10%	C6	60%	C10	10%	C3	20%
	C8	10%	C7	10%	C14	20%	C4	60%
10	C9	10%	C8	70%	C3	10%	C5	10%
	C10	10%	C9	10%	C7	70%	C6	10%
	C11	10%	C10	10%	C11	10%	C7	70%
	C12	70%	C11	10%	C15	10%	C8	10%
11	C13	50%	C12	0%	C4	25%	C9	50%
	C14	0%	C13	50%	C8	25%	C10	0%
	C15	0%	C14	0%	C12	50%	C11	25%
	C16	50%	C15	50%	C16	0%	C12	25%
Write Direction	MSB-LSB		Random		LSB-MSB		LSB-MSB	
			Rolling C's		Random		Rolling Groups of 4	

FIG. 29A

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Binary Code to Cassette Table (by Lot#) (Variable) (X = Not applicable)											
Binary Code	Lot 1		Lot 2		Lot 3		Lot 4		...	Lot N	
	C#	%	C#	%	C#	%	C#	%		C#	%
00	C1	10%	C1	10%	C1	10%	C1	10%		C1	5%
	C2	40%	C2	40%	C2	40%	C2	30%		C2	5%
	C3	30%	C3	30%	C3	20%	C3	20%		C3	10%
	C4	20%	C4	10%	C4	10%	C4	10%		C4	10%
	X		C5	10%	C5	10%	C5	10%		C5	10%
	X		X		C6	10%	C6	10%		C6	10%
	X		X		X		C7	10%		C7	10%
	X		X		X		X			C8	10%
	X		X		X		X			C9	10%
	X		X		X		X			C10	20%
01	C5	60%	C6	60%	C7	40%	C8	30%		C11	5%
	C6	20%	C7	10%	C8	20%	C9	20%		C12	5%
	C7	10%	C8	10%	C9	10%	C10	10%		C13	5%
	C8	10%	C9	10%	C10	10%	C11	10%		C14	5%
	X		C10	10%	C11	10%	C12	10%		C15	10%
	X		X		C12	10%	C13	10%		C16	10%
	X		X		X		C14	10%		C17	10%
	X		X		X		X			C18	15%
	X		X		X		X			C19	15%
	X		X		X		X			C20	20%
10	C9	10%	C11	10%	C13	10%	C15	10%		C21	5%
	C10	10%	C12	10%	C14	10%	C16	10%		C22	5%
	C11	10%	C13	10%	C15	10%	C17	10%		C23	5%
	C12	70%	C14	60%	C16	50%	C18	40%		C24	5%
	X		C15	10%	C17	10%	C19	10%		C25	5%
	X		X		C18	10%	C20	10%		C26	10%
	X		X		X		C21	10%		C27	15%
	X		X		X		X			C28	15%
	X		X		X		X			C29	15%
	X		X		X		X			C30	20%
11	C13	50%	C16	0%	C19	25%	C22	50%		C31	10%
	C14	0%	C17	50%	C20	25%	C23	0%		C32	0%
	C15	0%	C18	0%	C21	40%	C24	20%		C33	10%
	C16	50%	C19	50%	C22	0%	C25	20%		C34	0%
	X		C20	0%	C23	0%	C26	0%		C35	10%
	X		X		C24	10%	C27	10%		C36	10%
	X		X		X		C28	0%		C37	10%
	X		X		X		X			C38	15%
	X		X		X		X			C39	15%
	X		X		X		X			C40	20%

FIG. 29B

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Binary Code to Cassette Table (10 Cassettes per bit pair) (X = Not used)											
Binary Code	Lot 1		Lot 2		Lot 3		Lot 4		...	Lot N	
	C#	%	C#	%	C#	%	C#	%		C#	%
00	C1	10%	C1	10%	C1	X	C1	X		C1	X
	C2	40%	C2	X	C2	10%	C2	X		C2	X
	C3	30%	C3	40%	C3	X	C3	10%		C3	X
	C4	20%	C4	X	C4	40%	C4	X		C4	X
	C5	X	C5	30%	C5	X	C5	40%		C5	X
	C6	X	C6	X	C6	30%	C6	X		C6	X
	C7	X	C7	20%	C7	X	C7	30%		C7	10%
	C8	X	C8	X	C8	20%	C8	X		C8	40%
	C9	X	C9	X	C9	X	C9	20%		C9	30%
	C10	X	C10	X	C10	X	C10	X		C10	20%
01	C11	60%	C11	60%	C11	X	C11	X		C11	X
	C12	20%	C12	X	C12	60%	C12	X		C12	X
	C13	10%	C13	20%	C13	X	C13	60%		C13	X
	C14	10%	C14	X	C14	20%	C14	X		C14	X
	C15	X	C15	10%	C15	X	C15	20%		C15	X
	C16	X	C16	X	C16	10%	C16	X		C16	X
	C17	X	C17	10%	C17	X	C17	10%		C17	60%
	C18	X	C18	X	C18	10%	C18	X		C18	20%
	C19	X	C19	X	C19	X	C19	10%		C19	10%
	C20	X	C20	X	C20	X	C20	X		C20	10%
10	C21	10%	C21	10%	C21	X	C21	X		C21	X
	C22	10%	C22	X	C22	10%	C22	X		C22	X
	C23	10%	C23	10%	C23	X	C23	10%		C23	X
	C24	70%	C24	X	C24	10%	C24	X		C24	X
	C25	X	C25	10%	C25	X	C25	10%		C25	X
	C26	X	C26	X	C26	10%	C26	X		C26	X
	C27	X	C27	70%	C27	X	C27	10%		C27	10%
	C28	X	C28	X	C28	70%	C28	X		C28	10%
	C29	X	C29	X	C29	X	C29	70%		C29	10%
	C30	X	C30	X	C30	X	C30	X		C30	70%
11	C31	50%	C31	10%	C31	X	C31	X		C31	X
	C32	0%	C32	X	C32	10%	C32	X		C32	X
	C33	0%	C33	10%	C33	X	C33	10%		C33	X
	C34	50%	C34	X	C34	10%	C34	X		C34	X
	C35	X	C35	10%	C35	X	C35	10%		C35	X
	C36	X	C36	X	C36	10%	C36	X		C36	X
	C37	X	C37	70%	C37	X	C37	10%		C37	10%
	C38	X	C38	X	C38	70%	C38	X		C38	10%
	C39	X	C39	X	C39	X	C39	70%		C39	10%
	C40	X	C40	X	C40	X	X	X		C40	70%

FIG. 29C

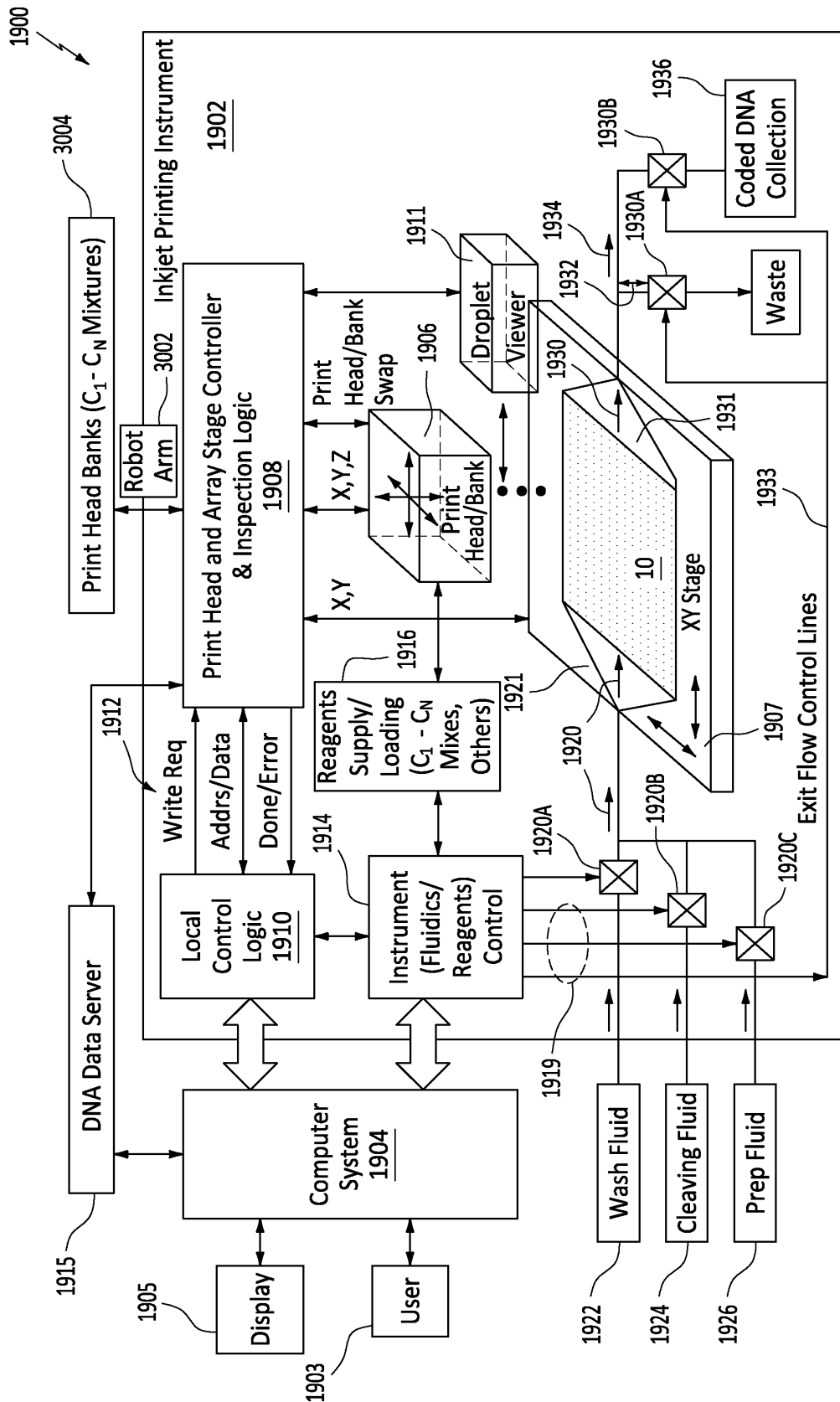


FIG. 30A

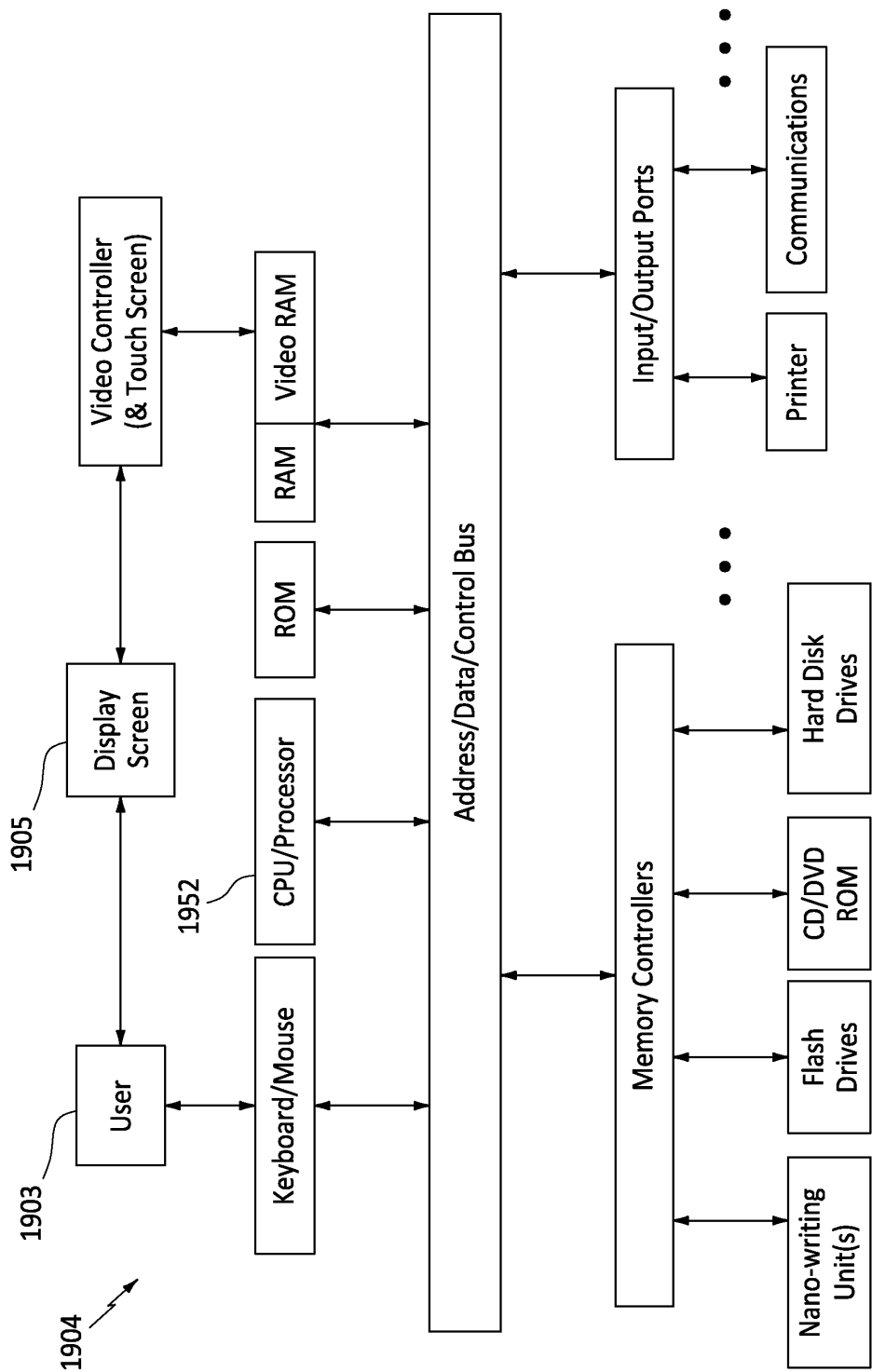


FIG. 30B

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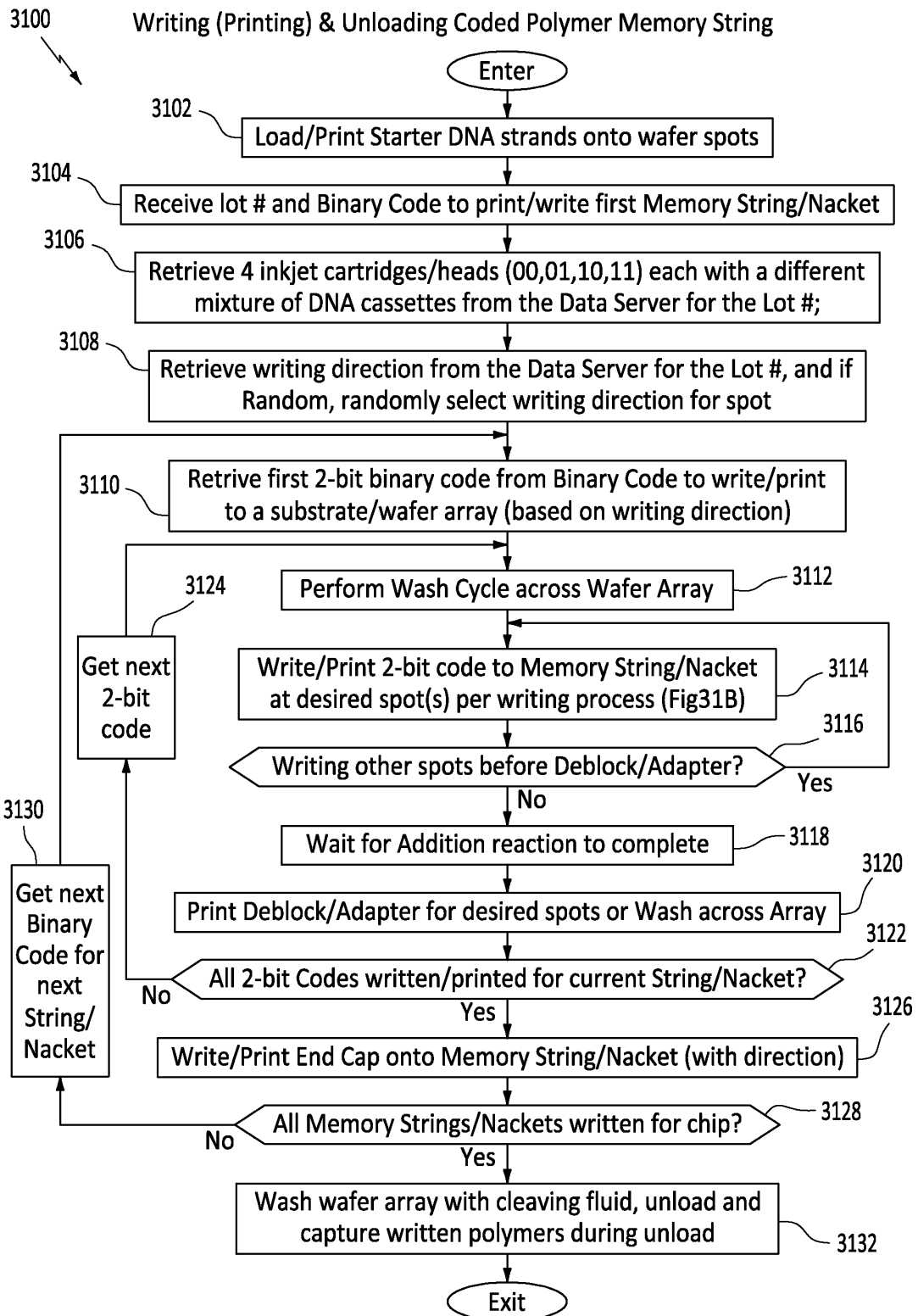


FIG. 31A

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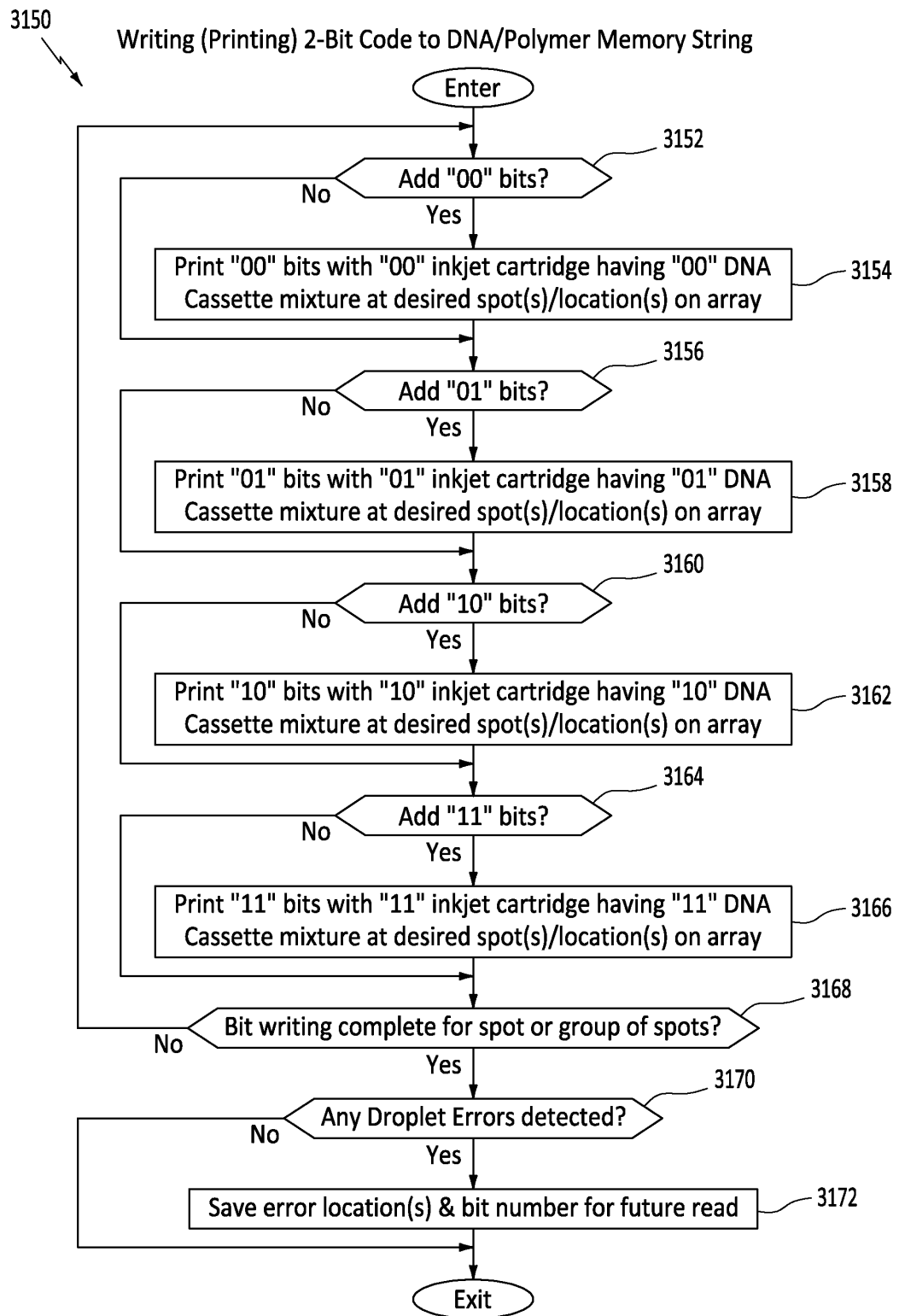


FIG. 31B

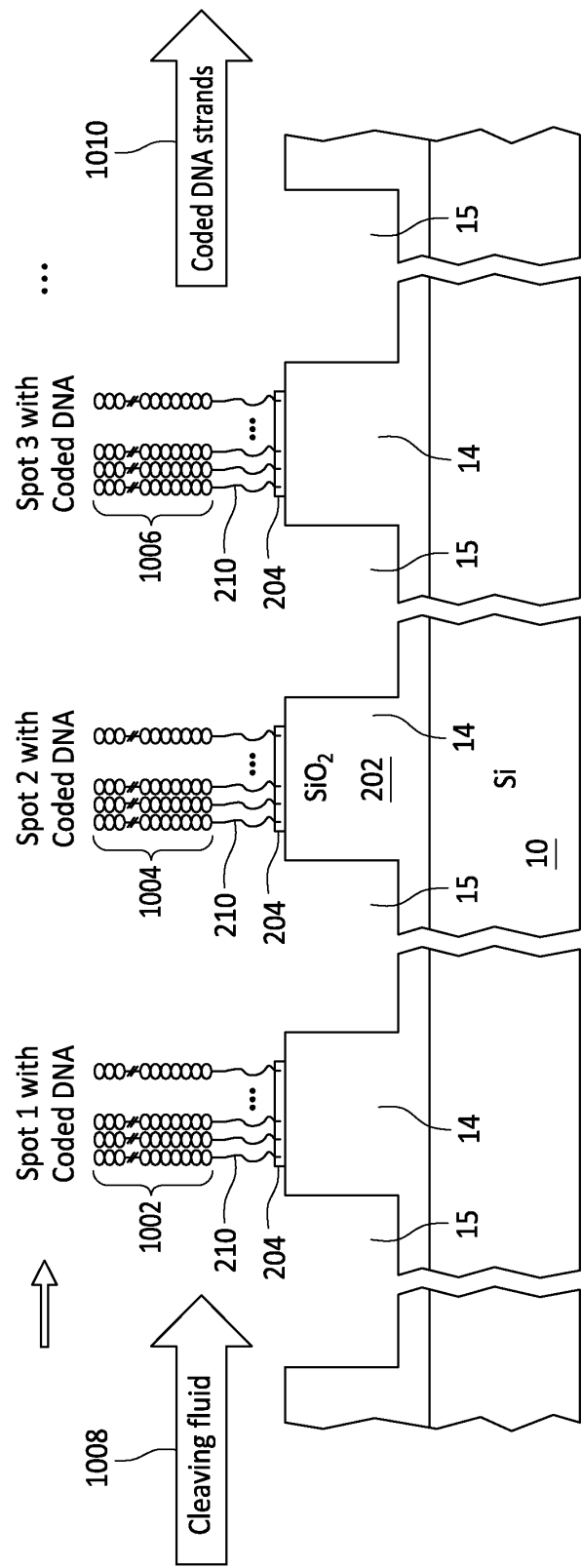


FIG. 32A

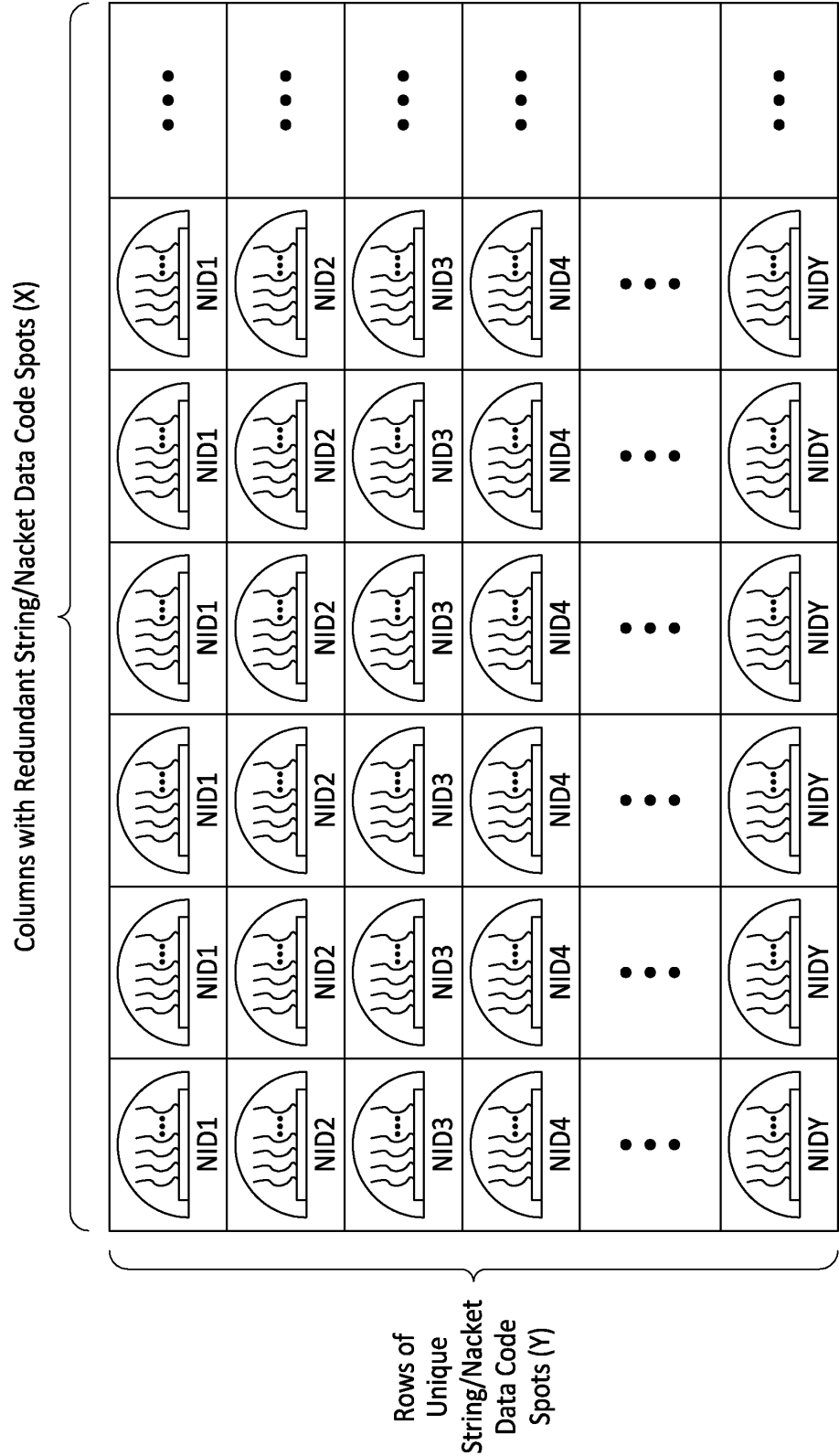


FIG. 32B

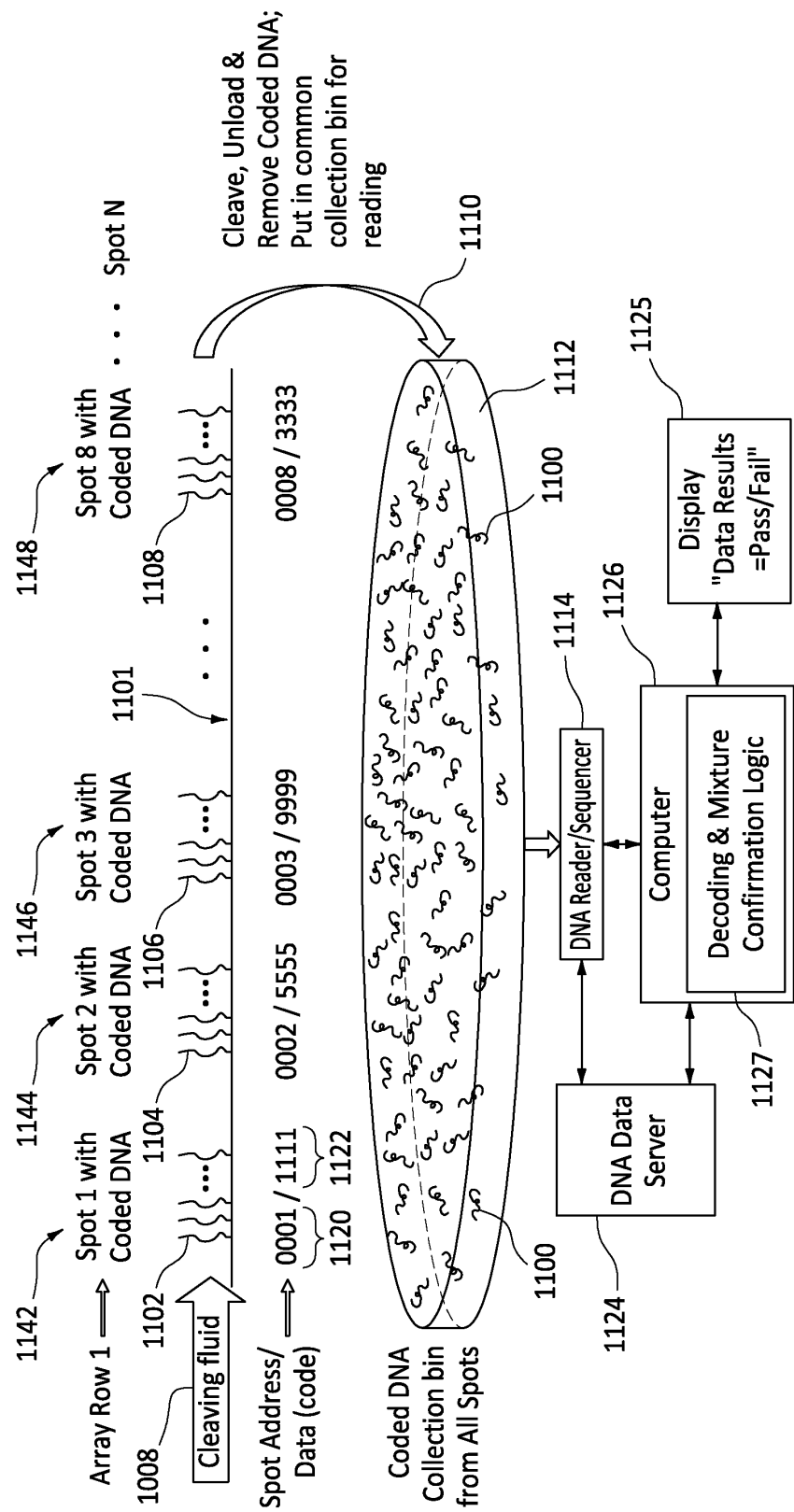


FIG. 33

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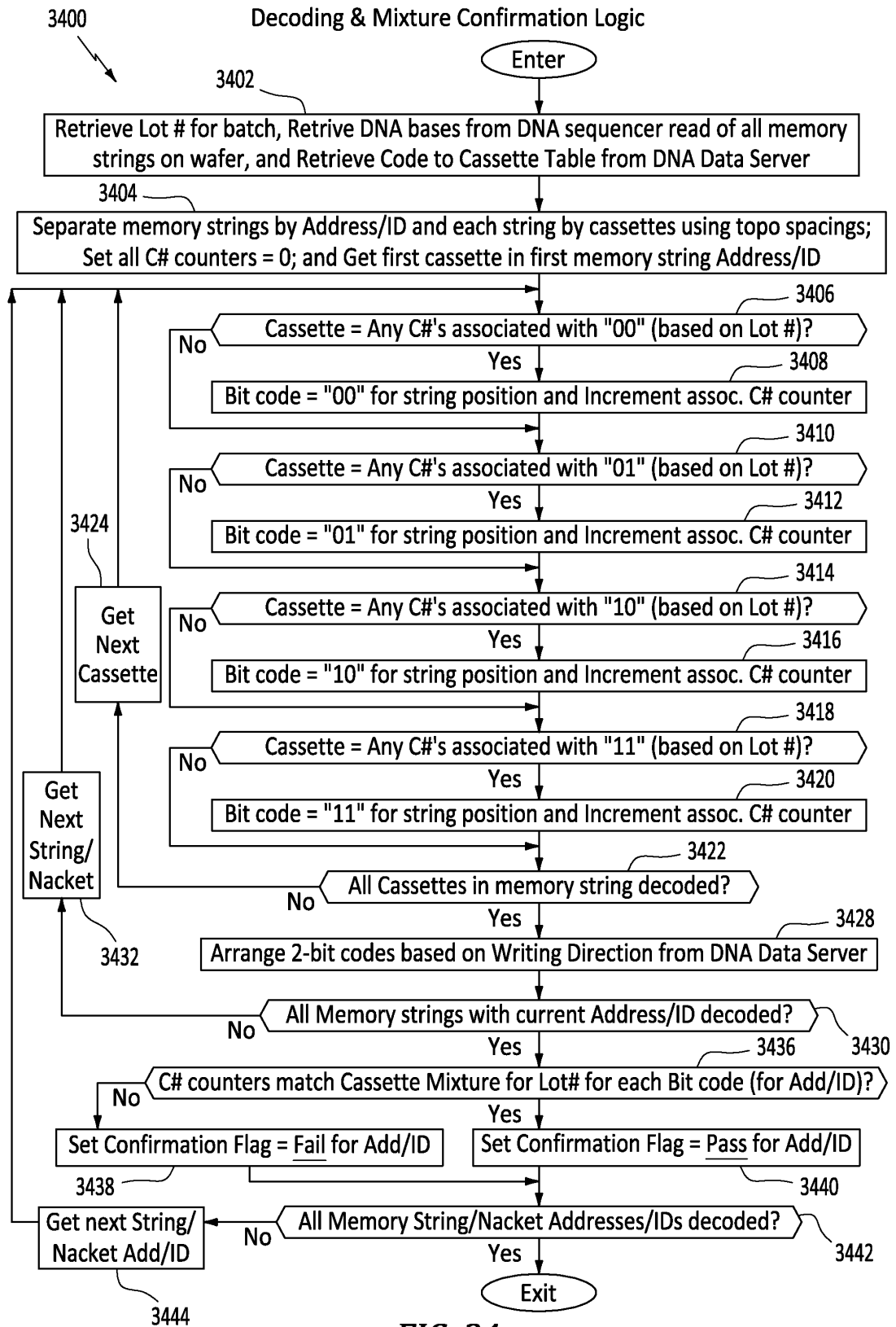
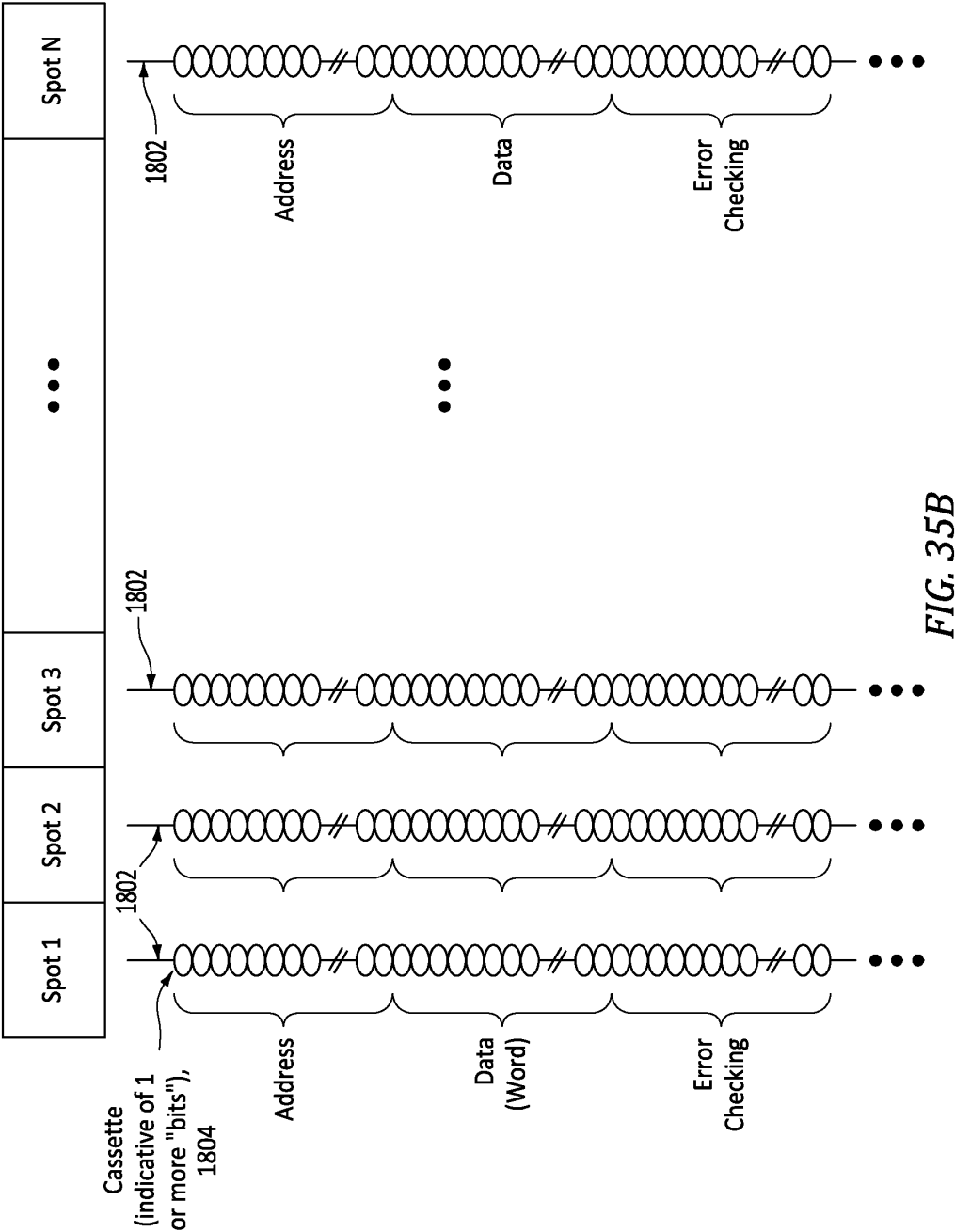


FIG. 34

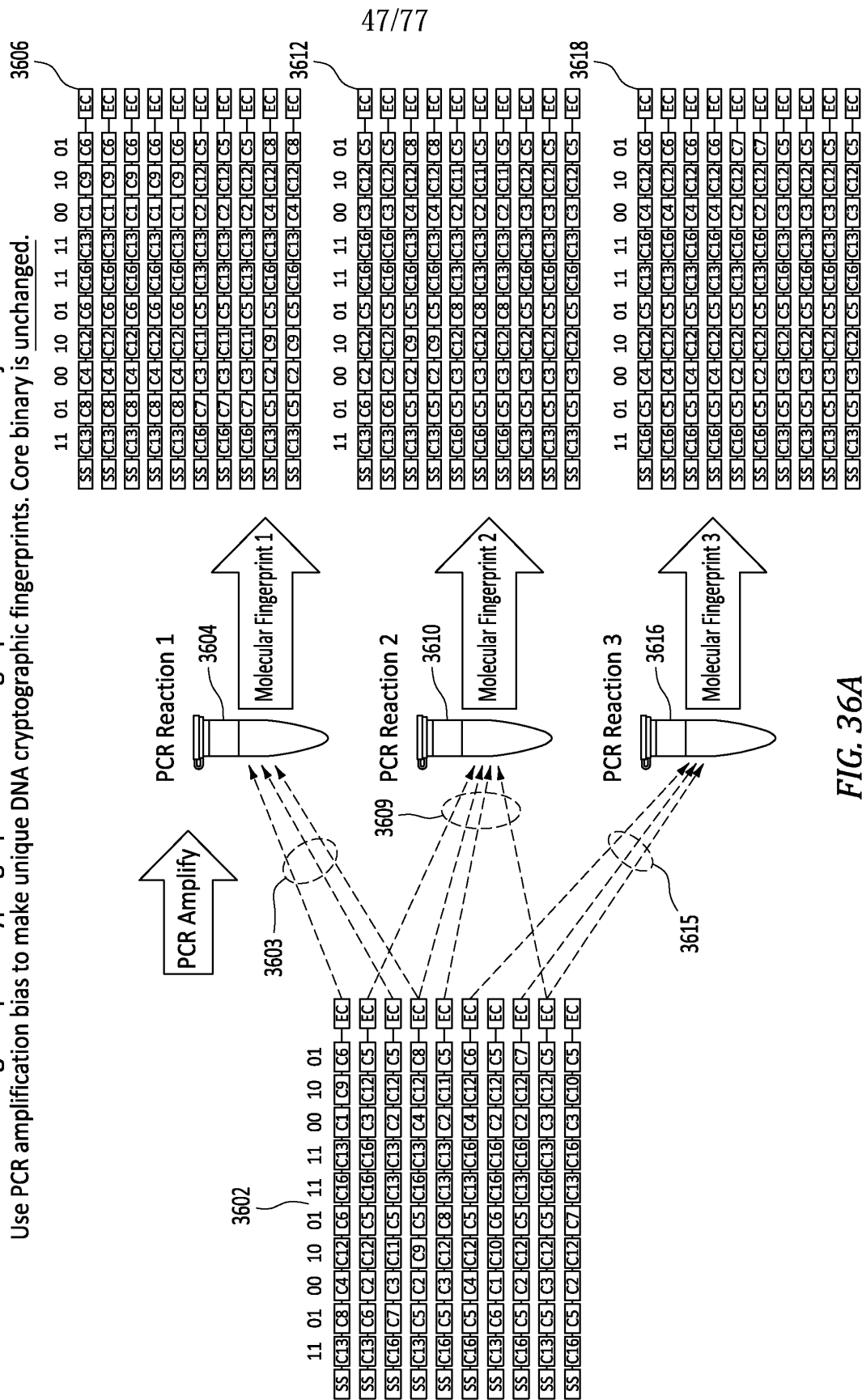


FIG. 35A



Creating unique "cryptographic" DNA fingerprints to embed into objects

Use PCR amplification bias to make unique DNA cryptographic fingerprints. Core binary is unchanged.



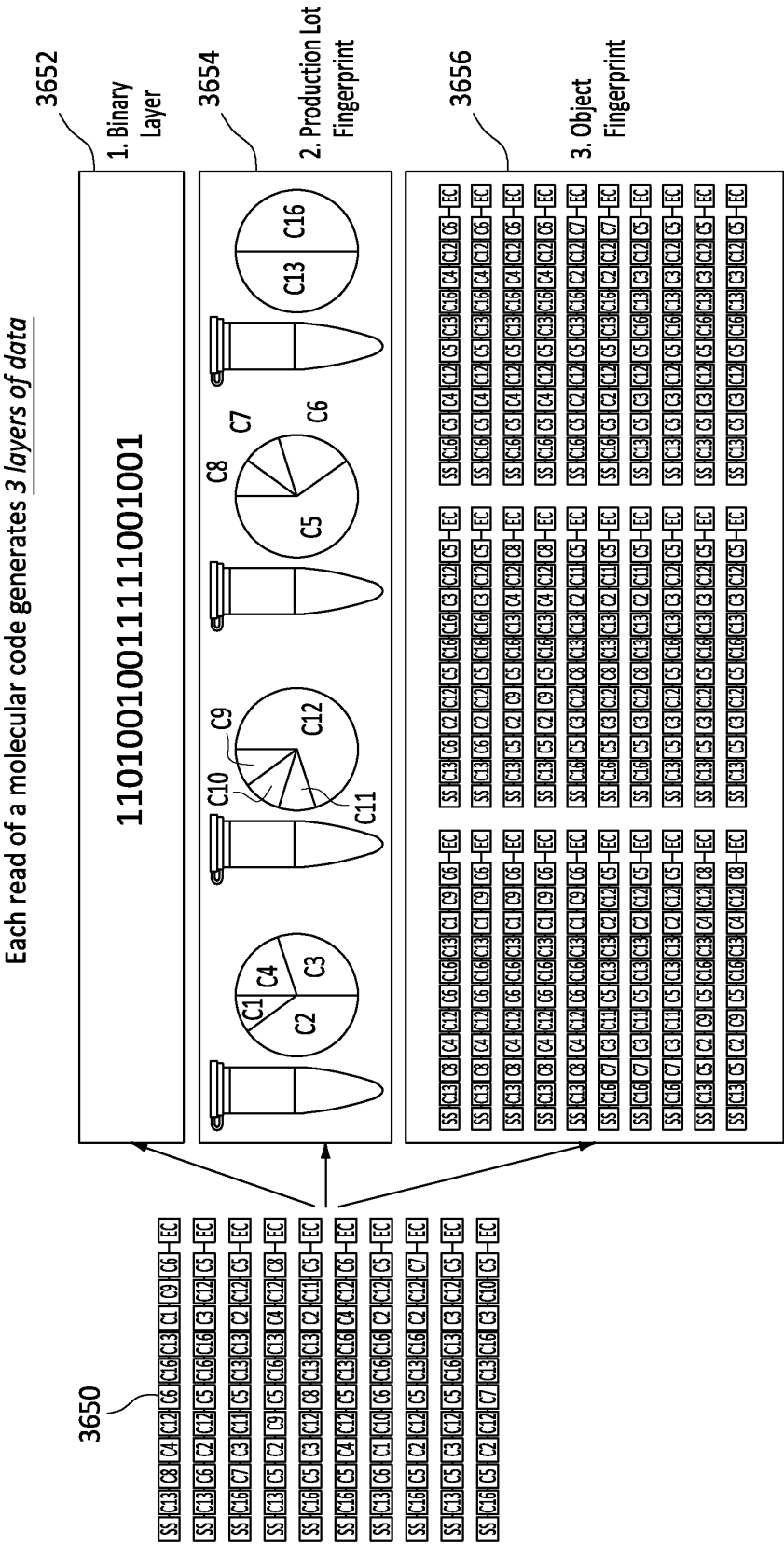


FIG. 36B

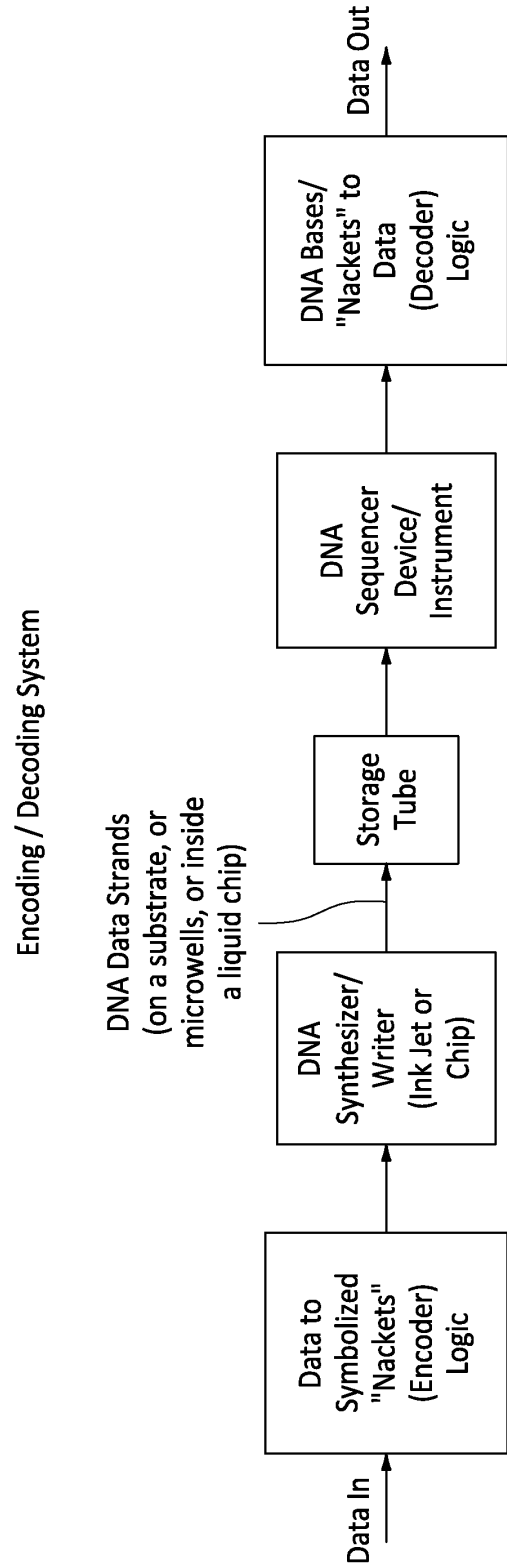


FIG. 37

Data Encoding Pipeline

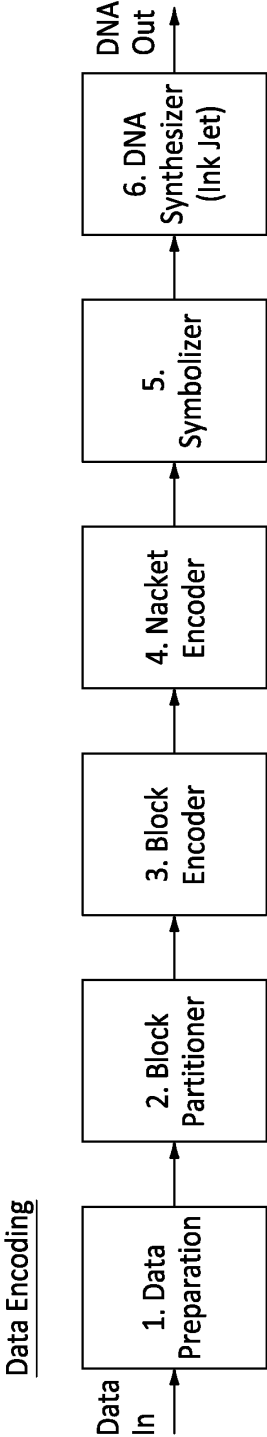


FIG. 38A

Data Encoding Pipeline

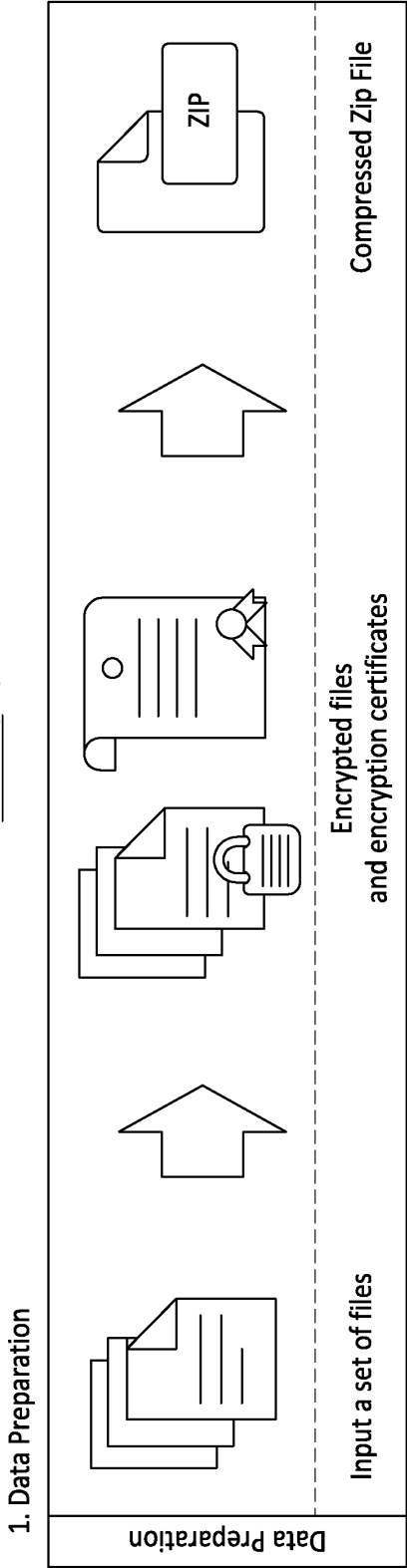


FIG. 38B

2. Block Partitioner

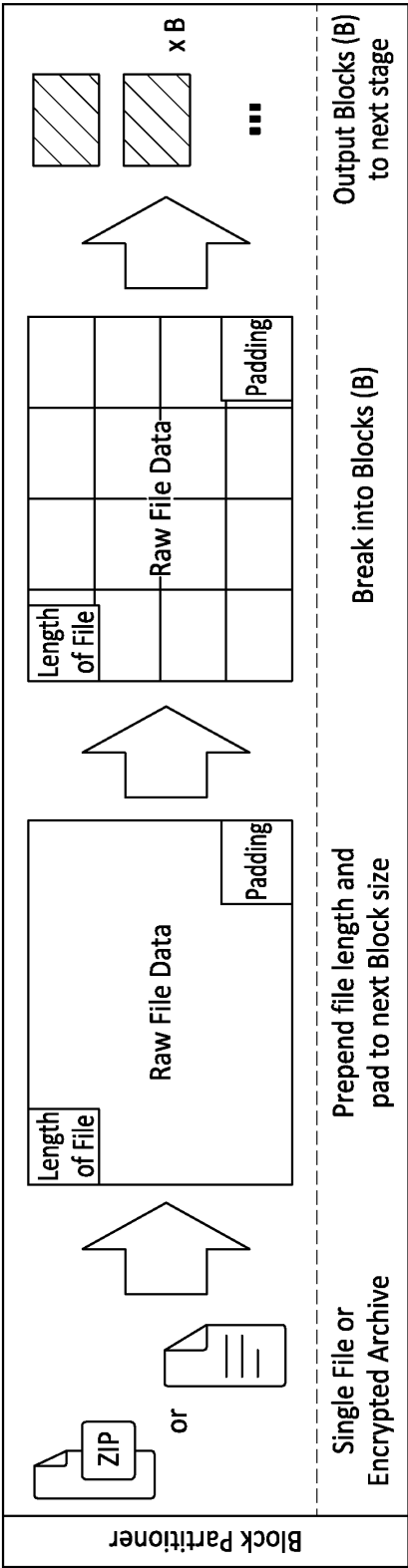


FIG. 38C

Data Encoding Pipeline (Cont.)

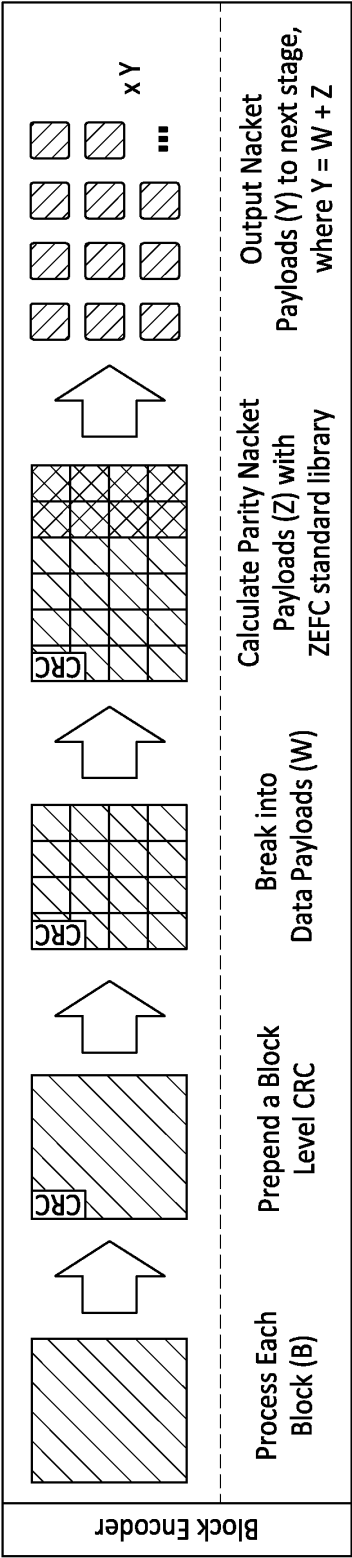


FIG. 38D

4. Nacket Encoder

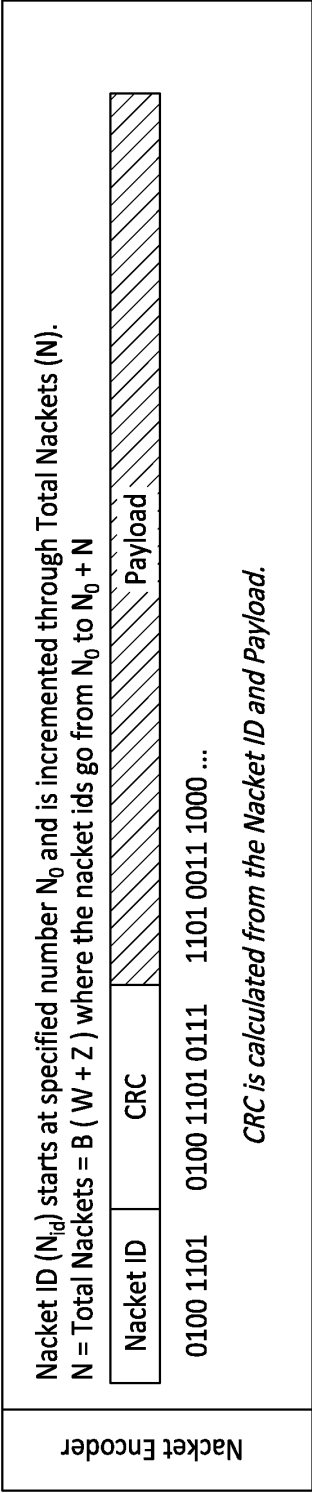
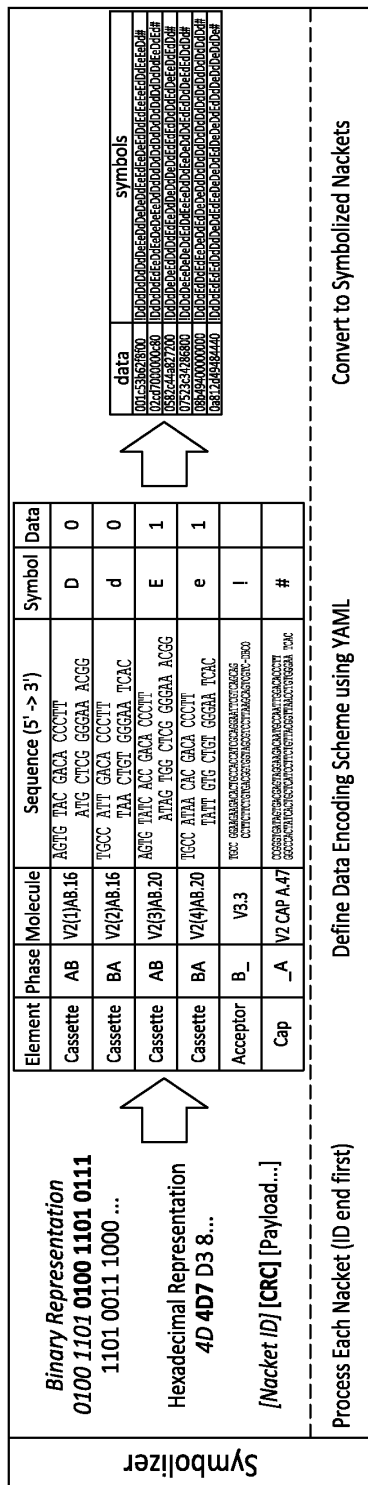


FIG. 38E

5. Symbolizer

Data Encoding Pipeline (Cont.)



OR

5. Symbolizer

Original Payload:
110100100111
1001001

Convert Binary Code to Cassettes (Cs) to be written (using 2-bit encoding)

Binary Code	Ln ¹ Chr %	Ln ² Chr %	Ln ³ Chr %	Ln ⁴ Chr %
00	C1 10%	C16 20%	C1 30%	C13 10%
	C2 40%	C1 30%	C5 20%	C14 20%
	C3 30%	C2 40%	C9 10%	C15 40%
	C4 20%	C3 40%	C13 40%	C16 30%
01	C5 60%	C4 20%	C2 10%	C1 10%
	C6 20%	C5 10%	C6 60%	C2 10%
	C7 10%	C6 60%	C10 10%	C3 20%
	C8 10%	C7 10%	C14 20%	C4 60%
10	C9 10%	C8 70%	C3 10%	C5 10%
	C10 10%	C9 10%	C7 70%	C6 10%
	C11 10%	C10 10%	C11 10%	C7 70%
	C12 70%	C11 10%	C15 10%	C8 10%
11	C13 50%	C12 0%	C4 25%	C9 50%
	C14 0%	C13 50%	C8 25%	C10 0%
	C15 0%	C14 0%	C12 50%	C11 25%
	C16 50%	C15 50%	C16 0%	C12 25%
Write Direction	M5B-LSB	Random	LSB-M5B	LSB-M5B

Rolling Groups of 4
Random
Rolling Groups of 4

Binary code: 11 01 00 10 01 11 11 00 10 01

S	SS	C13	C8	C4	C12	C6	C16	C13	C1	C9	C6
U	SS	C13	C6	C2	C12	C5	C16	C16	C3	C12	C5
R	SS	C16	C7	C3	C11	C5	C13	C13	C2	C12	C5
F	SS	C13	C5	C2	C9	C5	C16	C13	C4	C12	C8
A	SS	C16	C5	C3	C12	C8	C13	C13	C2	C11	C5
C	SS	C16	C5	C4	C12	C5	C13	C16	C4	C12	C6
E	SS	C13	C6	C1	C10	C6	C16	C16	C2	C12	C5
	SS	C16	C5	C2	C12	C5	C13	C16	C2	C12	C7
	SS	C13	C5	C3	C12	C5	C16	C13	C3	C12	C5
	SS	C16	C5	C2	C12	C7	C13	C16	C5	C10	C5

Where Cassettes (Cs) are predefined strings of DNA bases (GCAT)

FIG. 38F

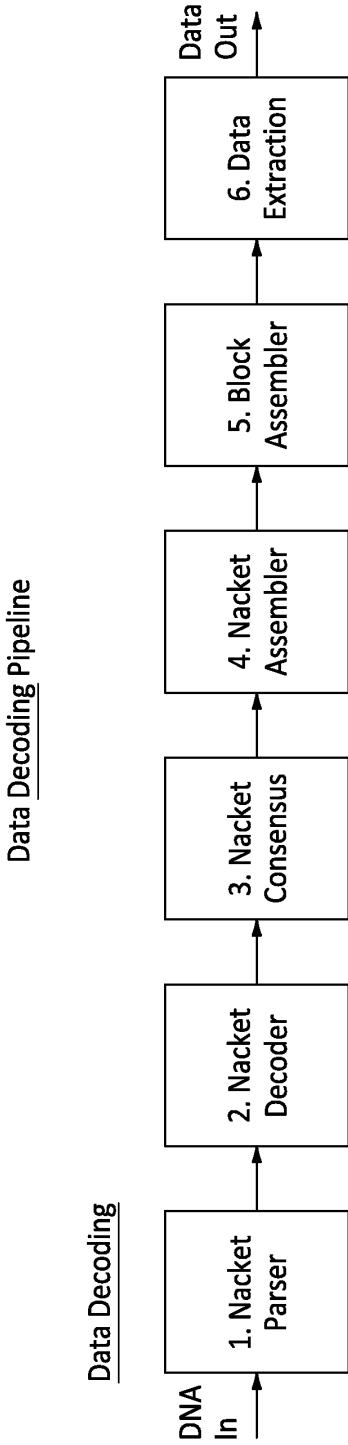


FIG. 39A

Data Decoding Pipeline (Cont.)

2. Nacket Decoder

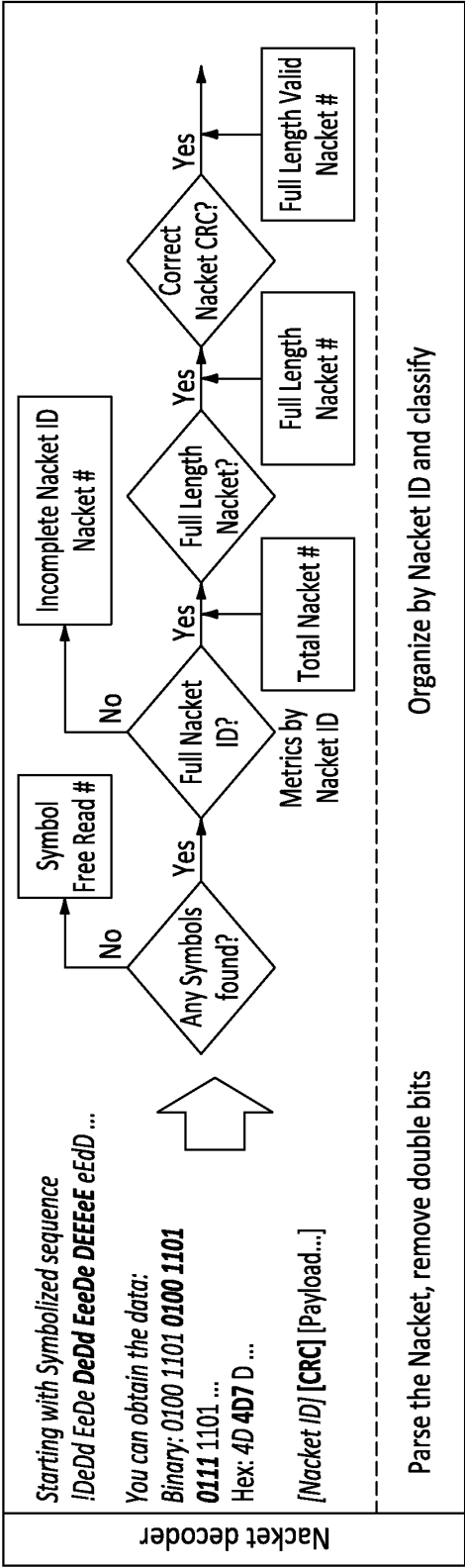


FIG. 39C

Data Decoding Pipeline (Cont.)

3. Nacket Consensus

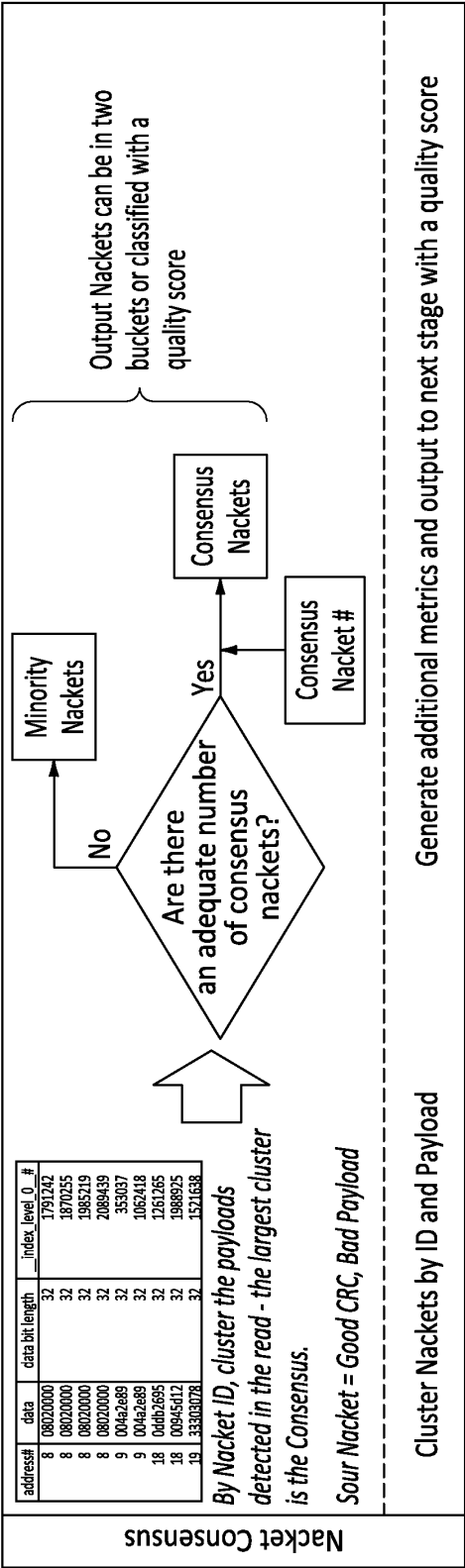


FIG. 39D

Data Decoding Pipeline (Cont.)

4. Nacket assembler

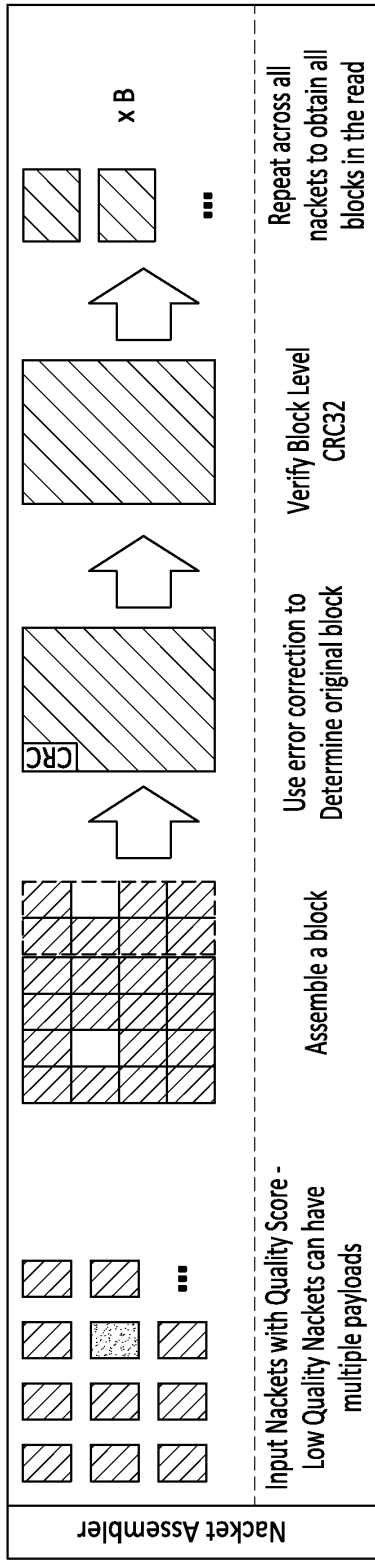


FIG. 39E

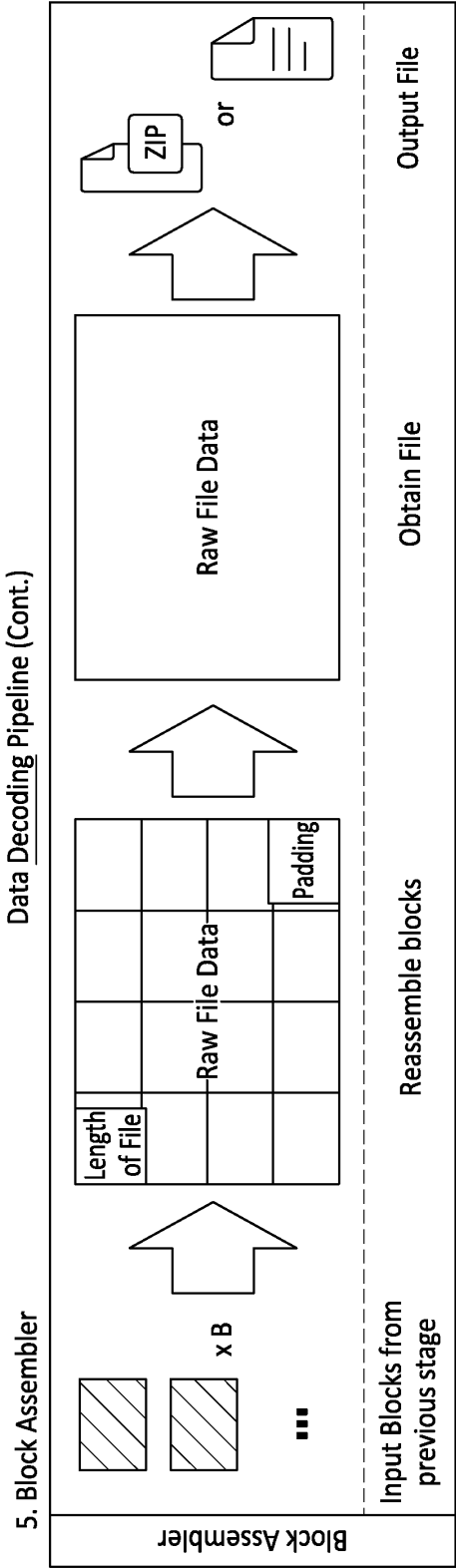


FIG. 39F

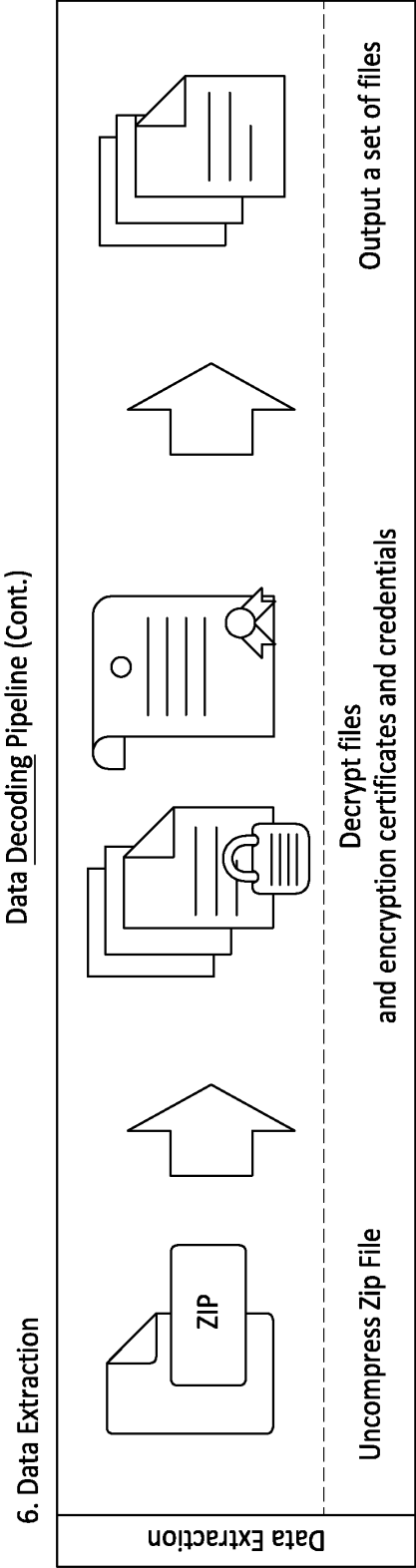


FIG. 39G

200 Byte Charts

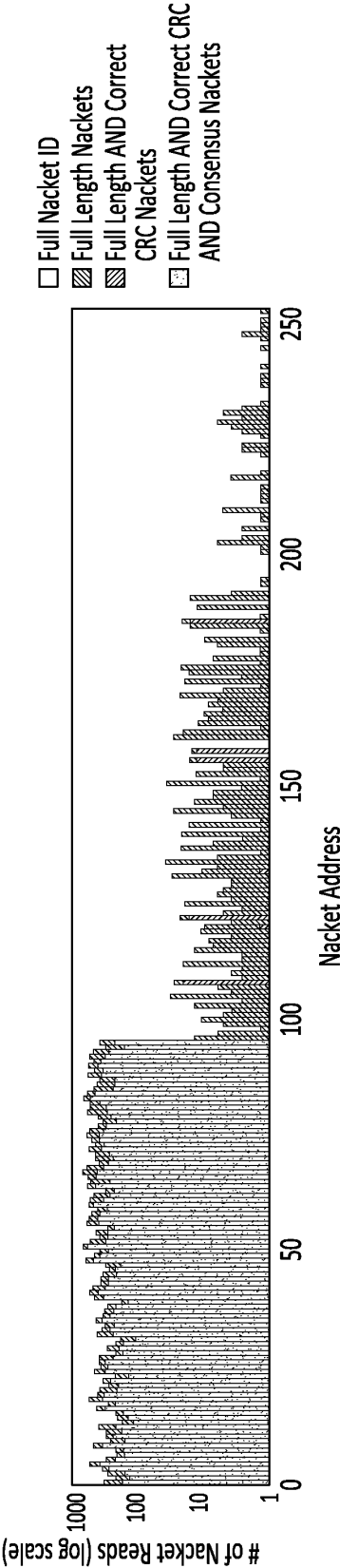


FIG. 40A

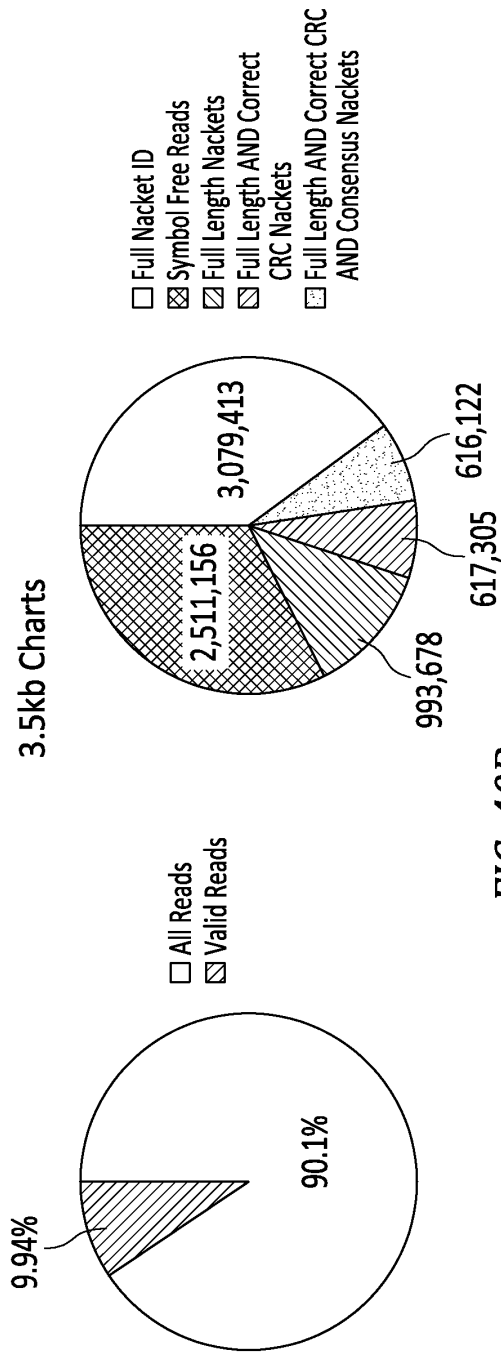


FIG. 40B

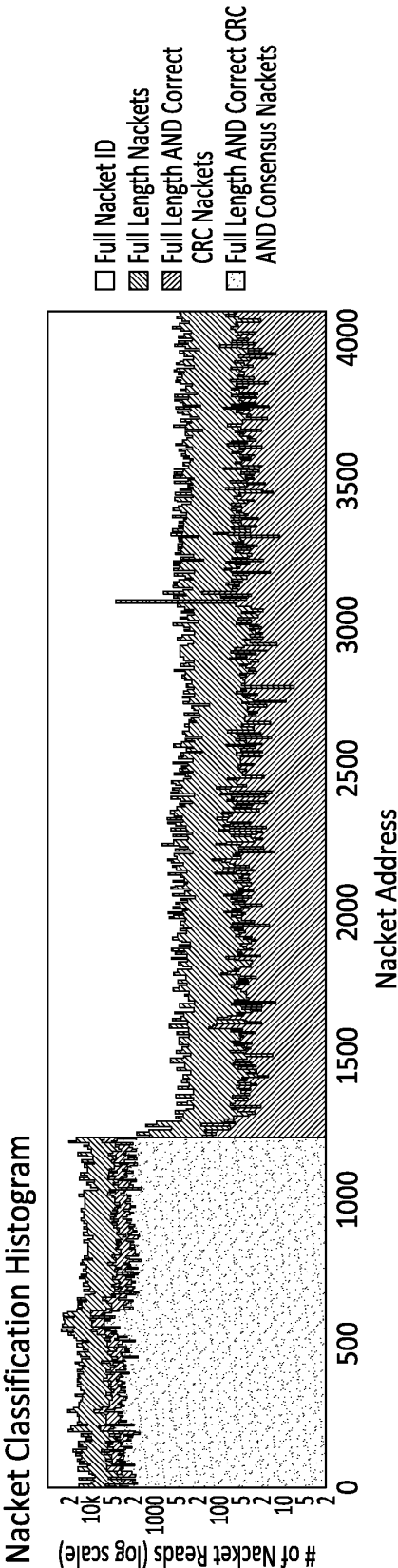


FIG. 40C



	A	C	G	T
A	n/a	2	1	0
C	0	n/a	2	1
G	1	0	n/a	2
T	2	1	0	n/a

FIG. 41

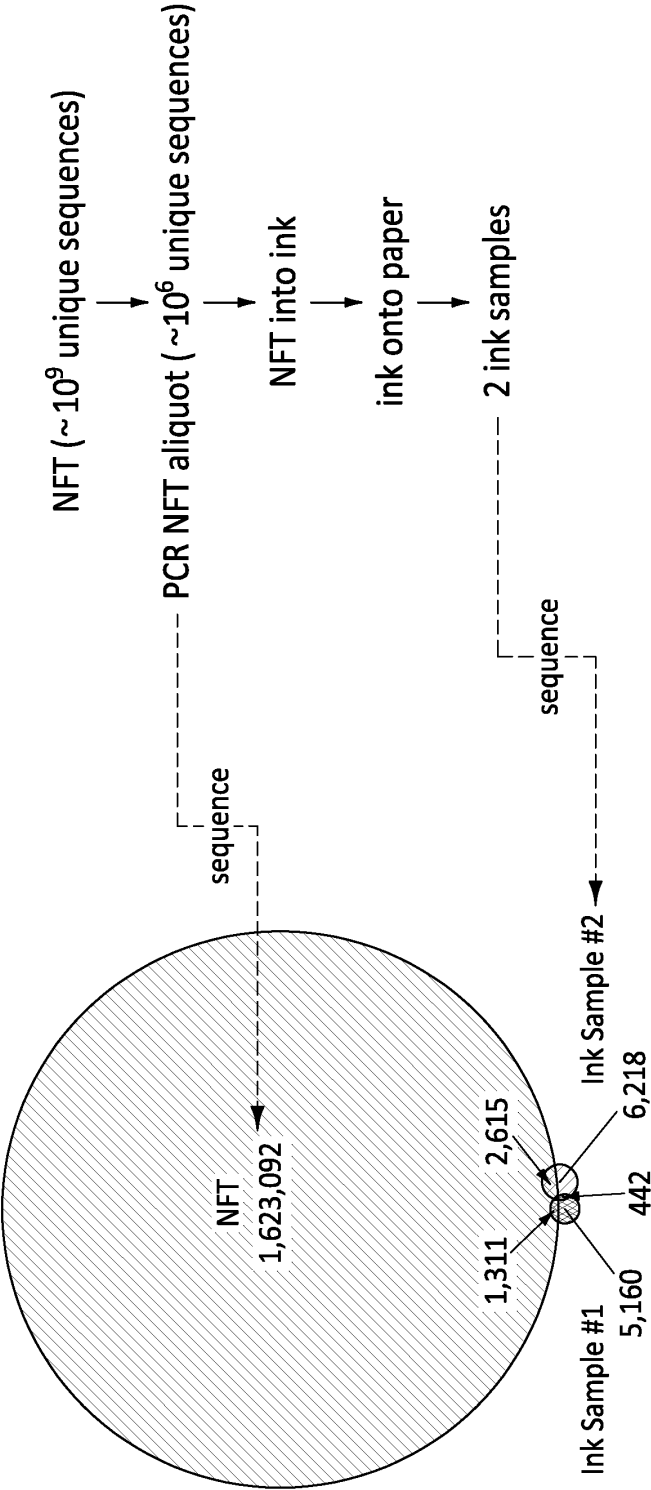


FIG. 42

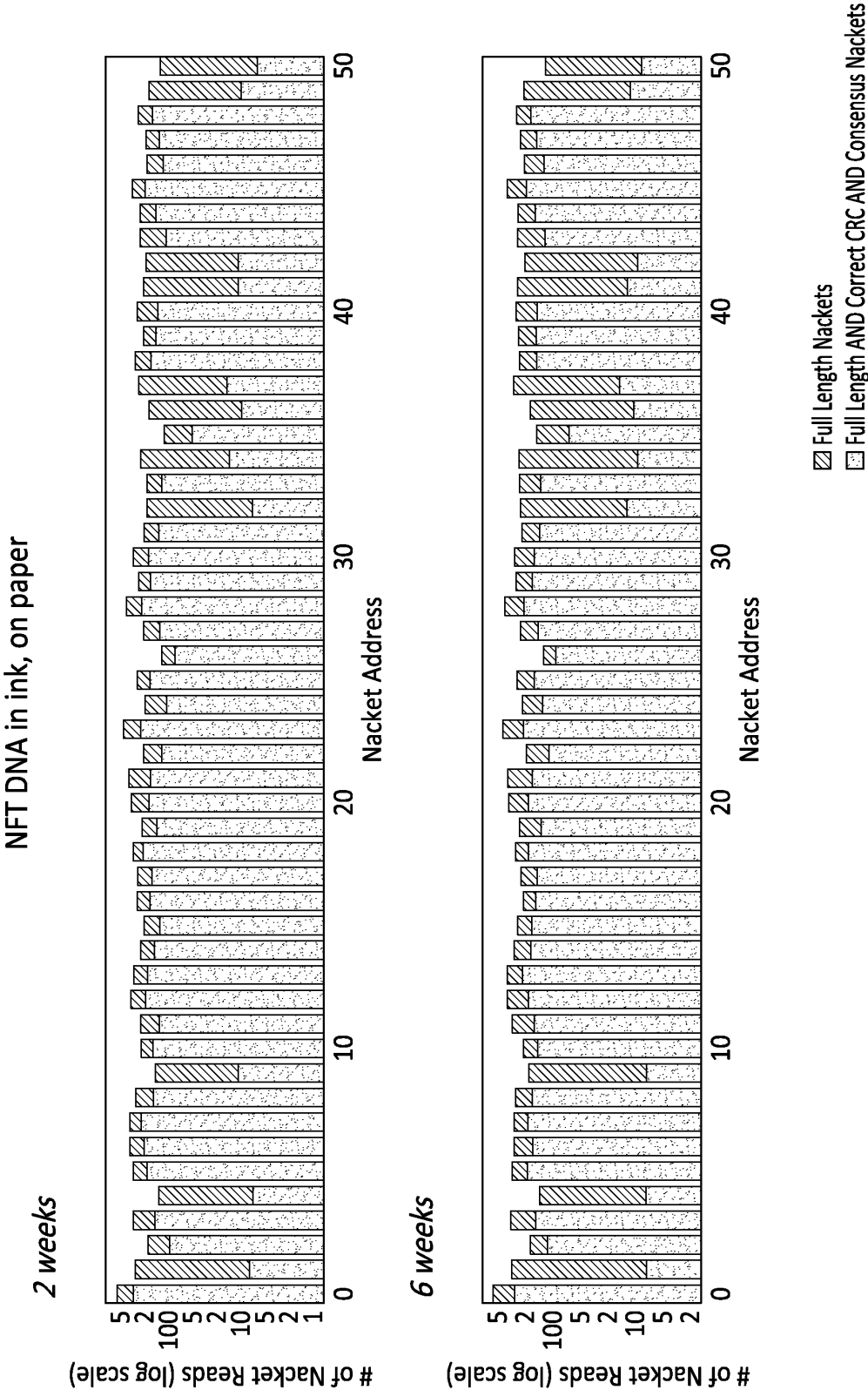
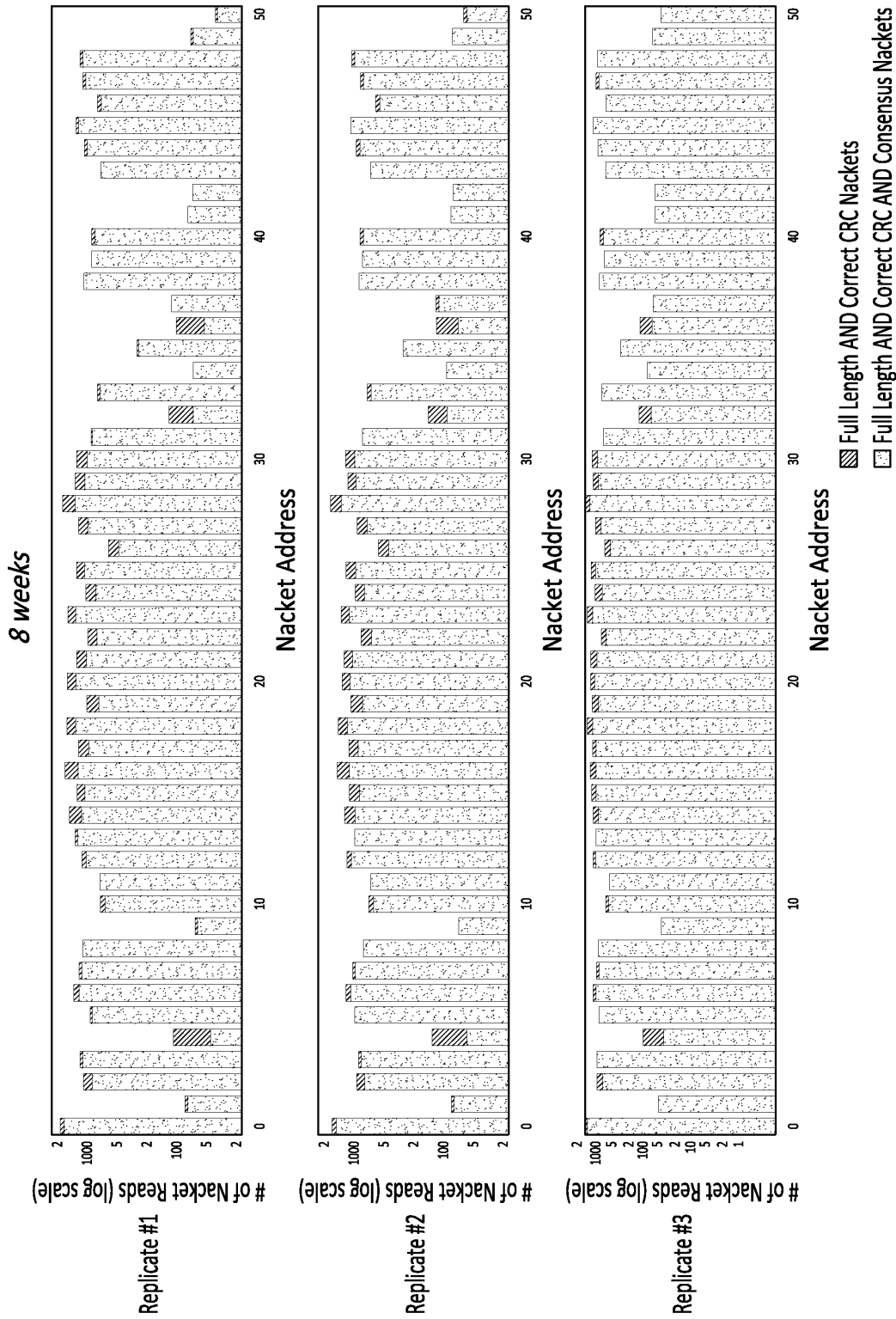


FIG. 43



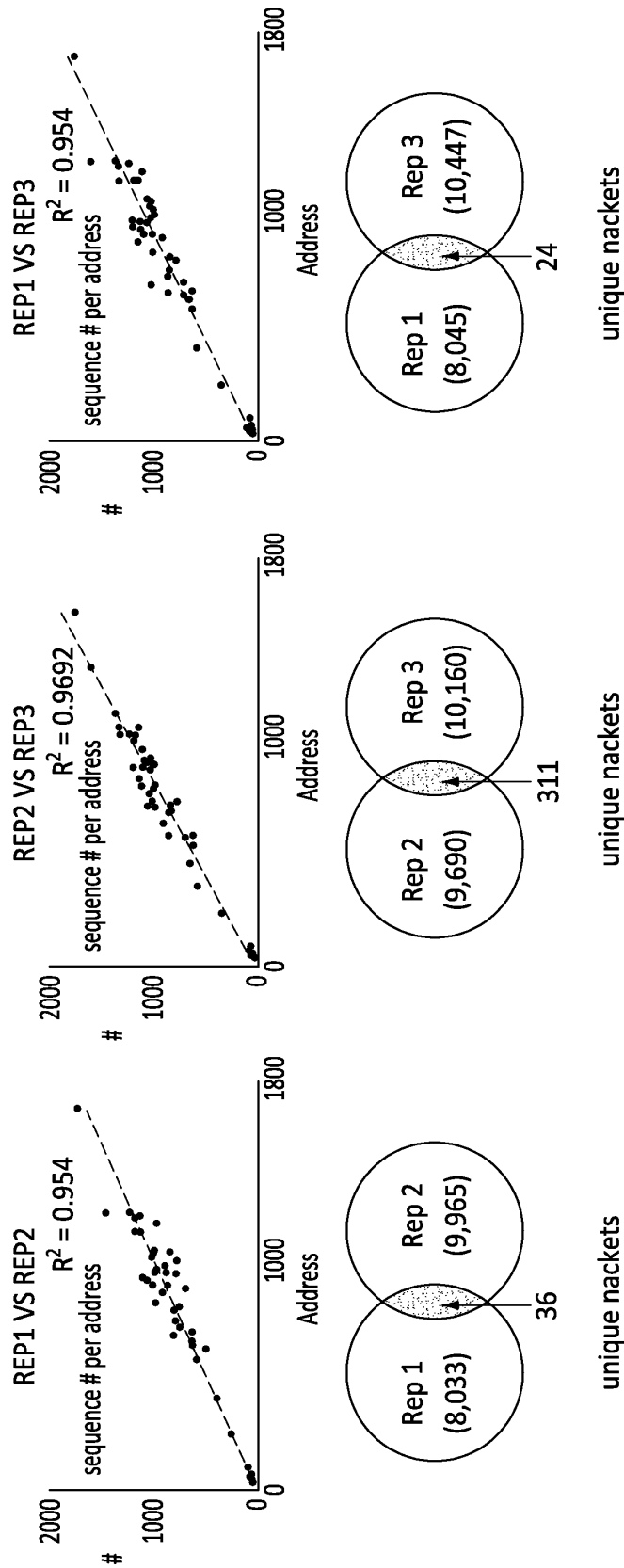


FIG. 45

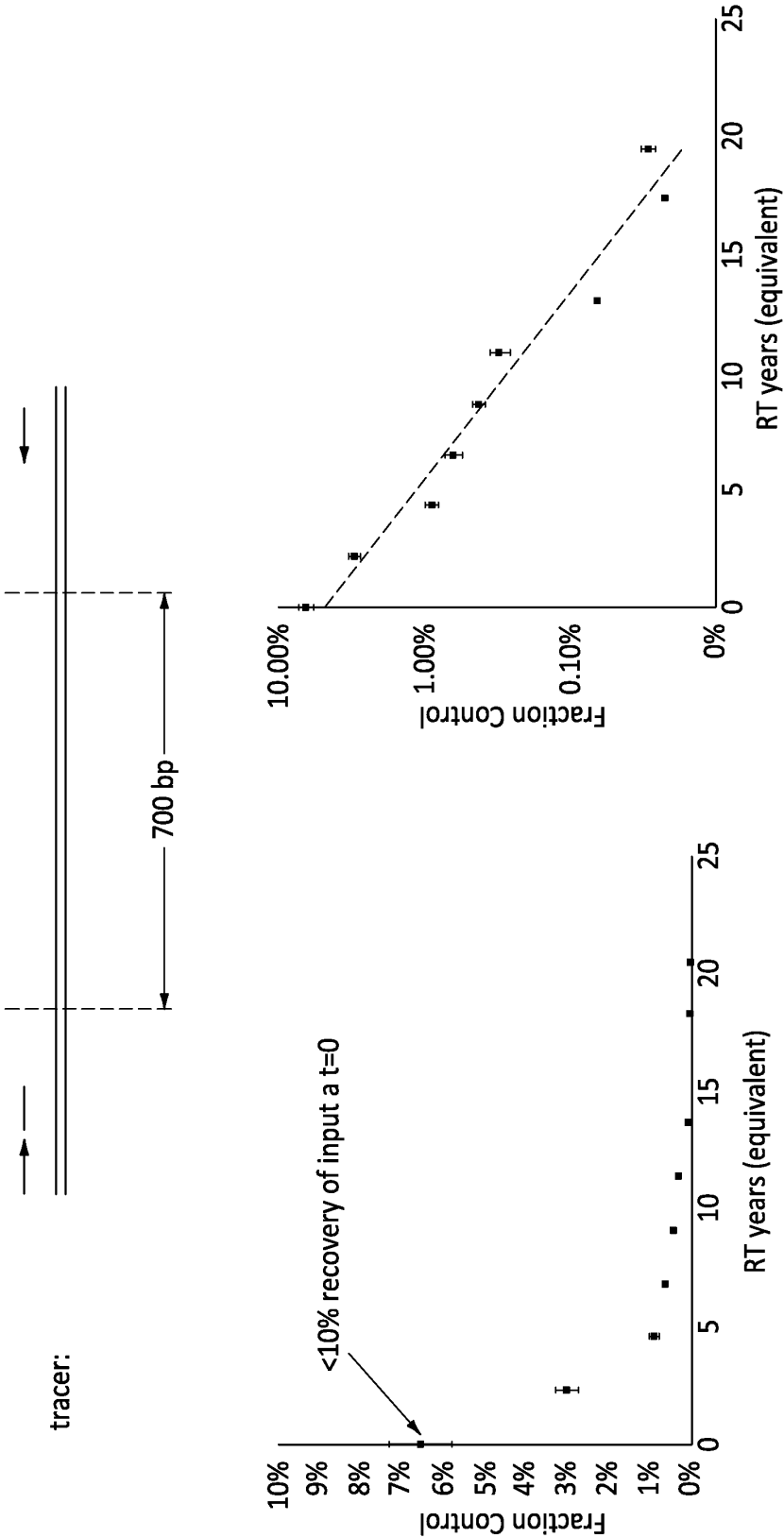


FIG. 46

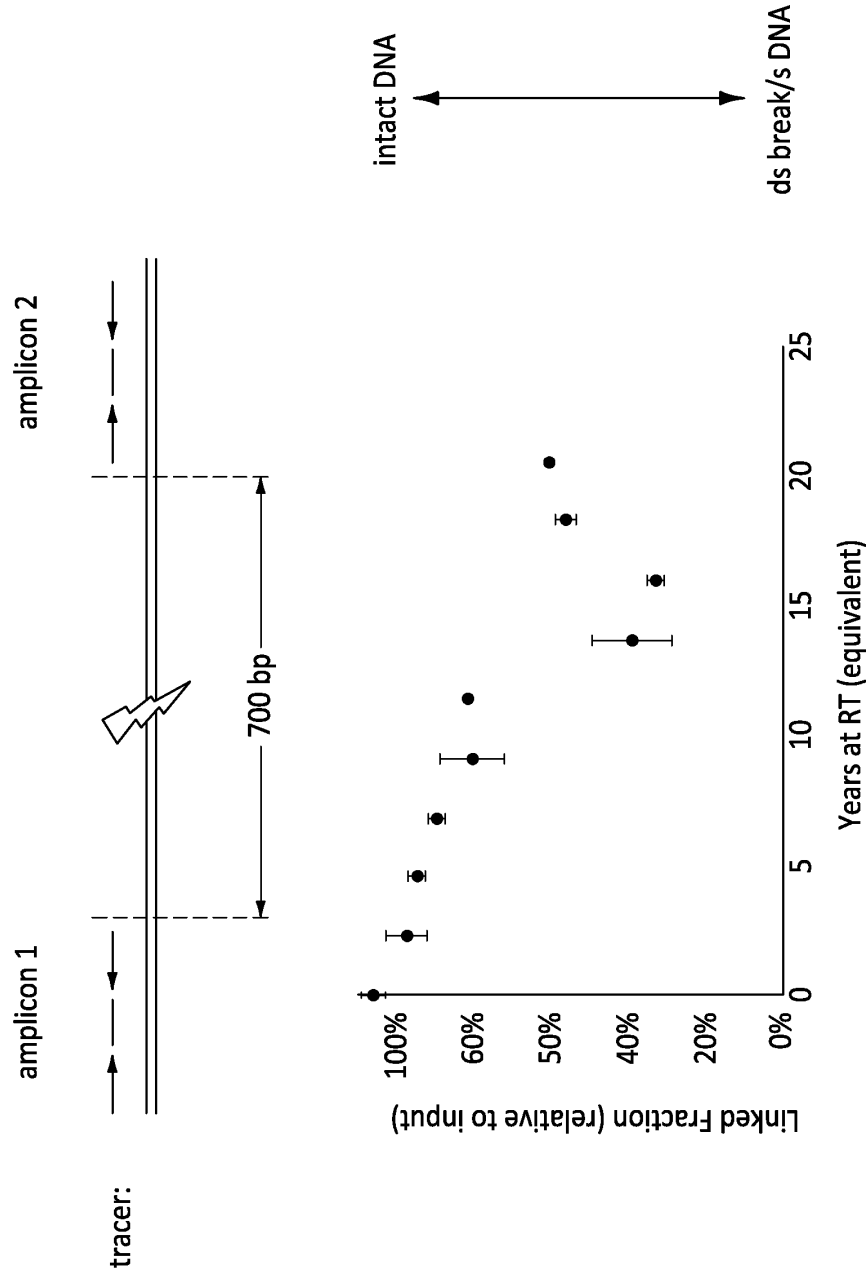


FIG. 47

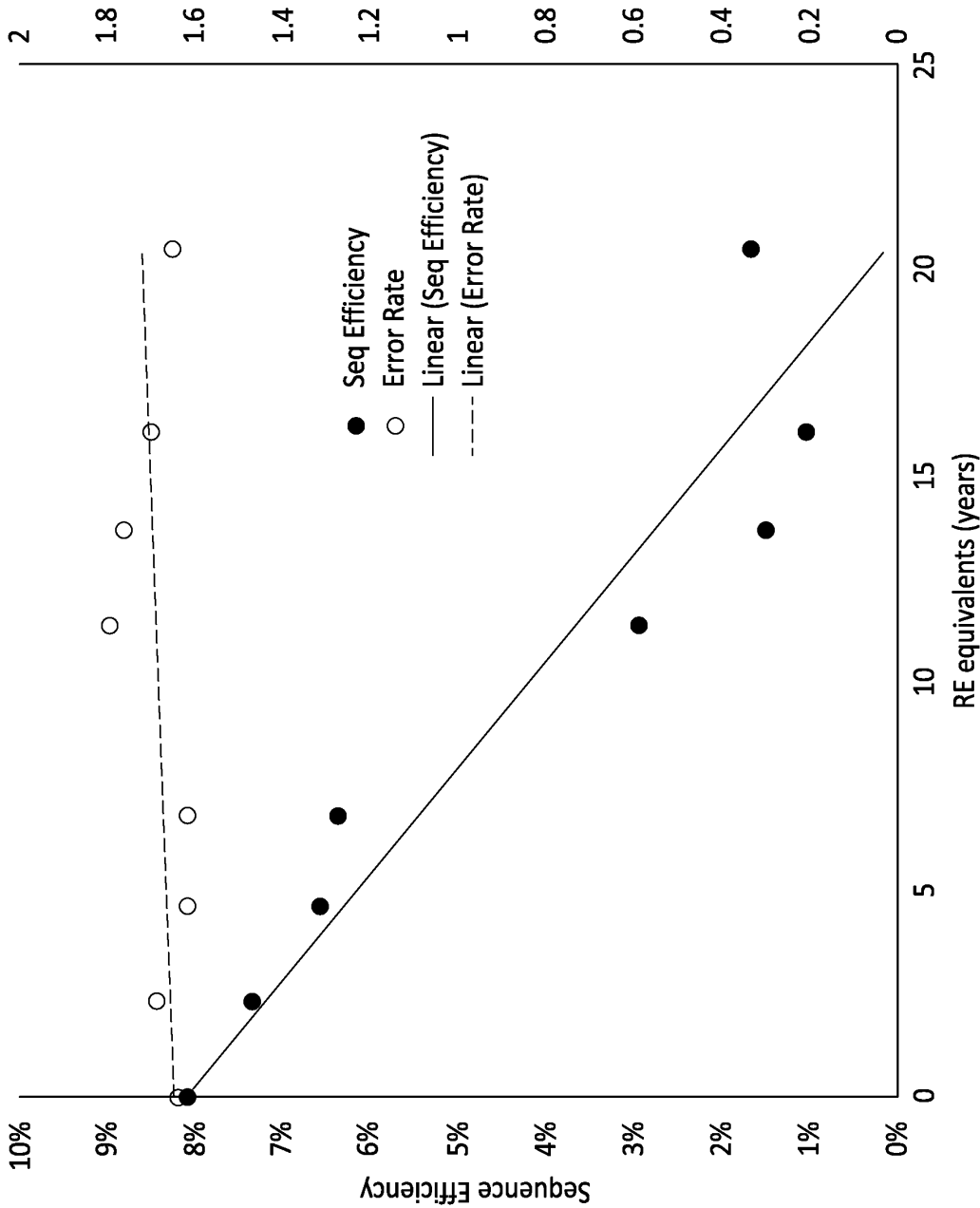


FIG. 48

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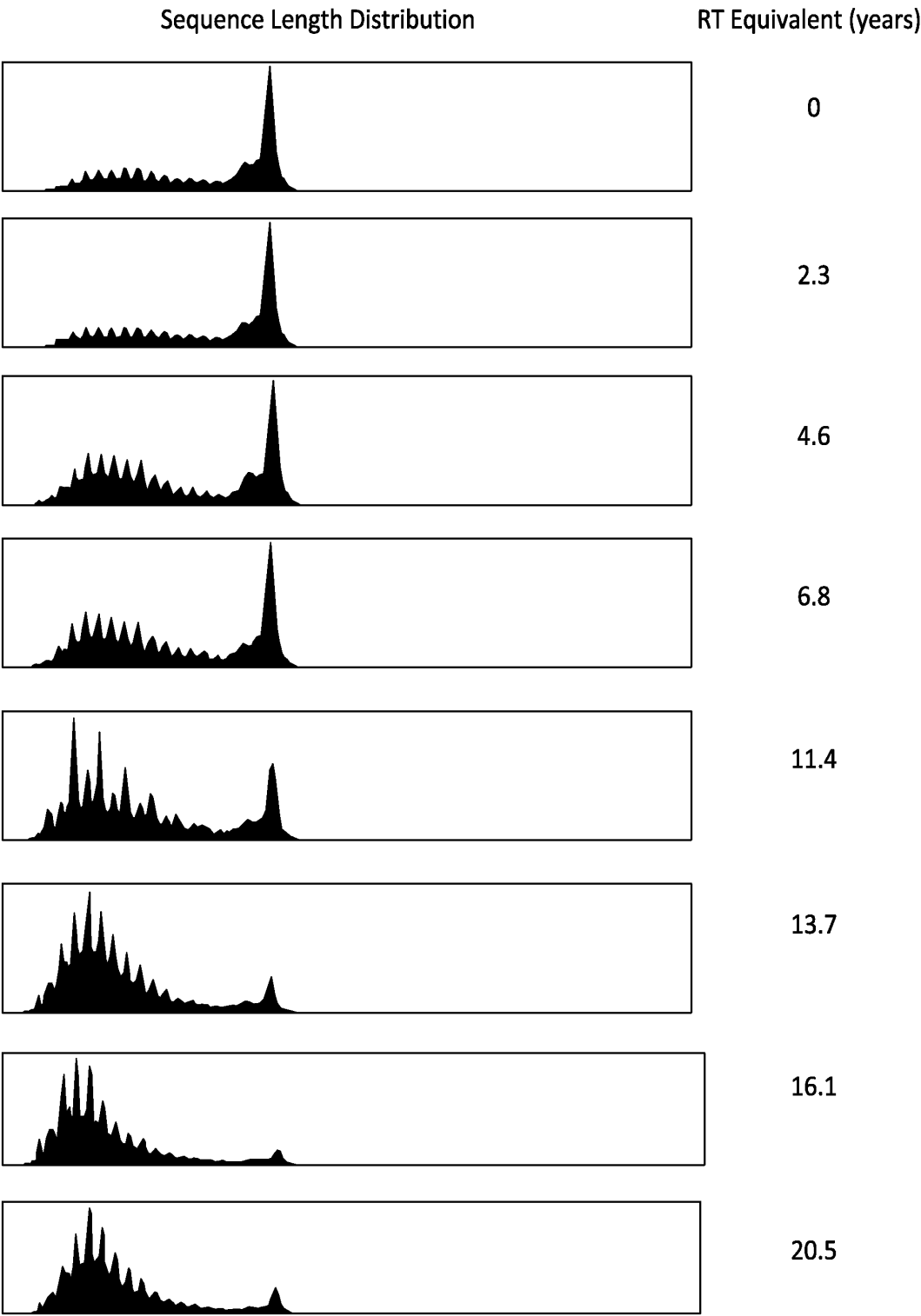
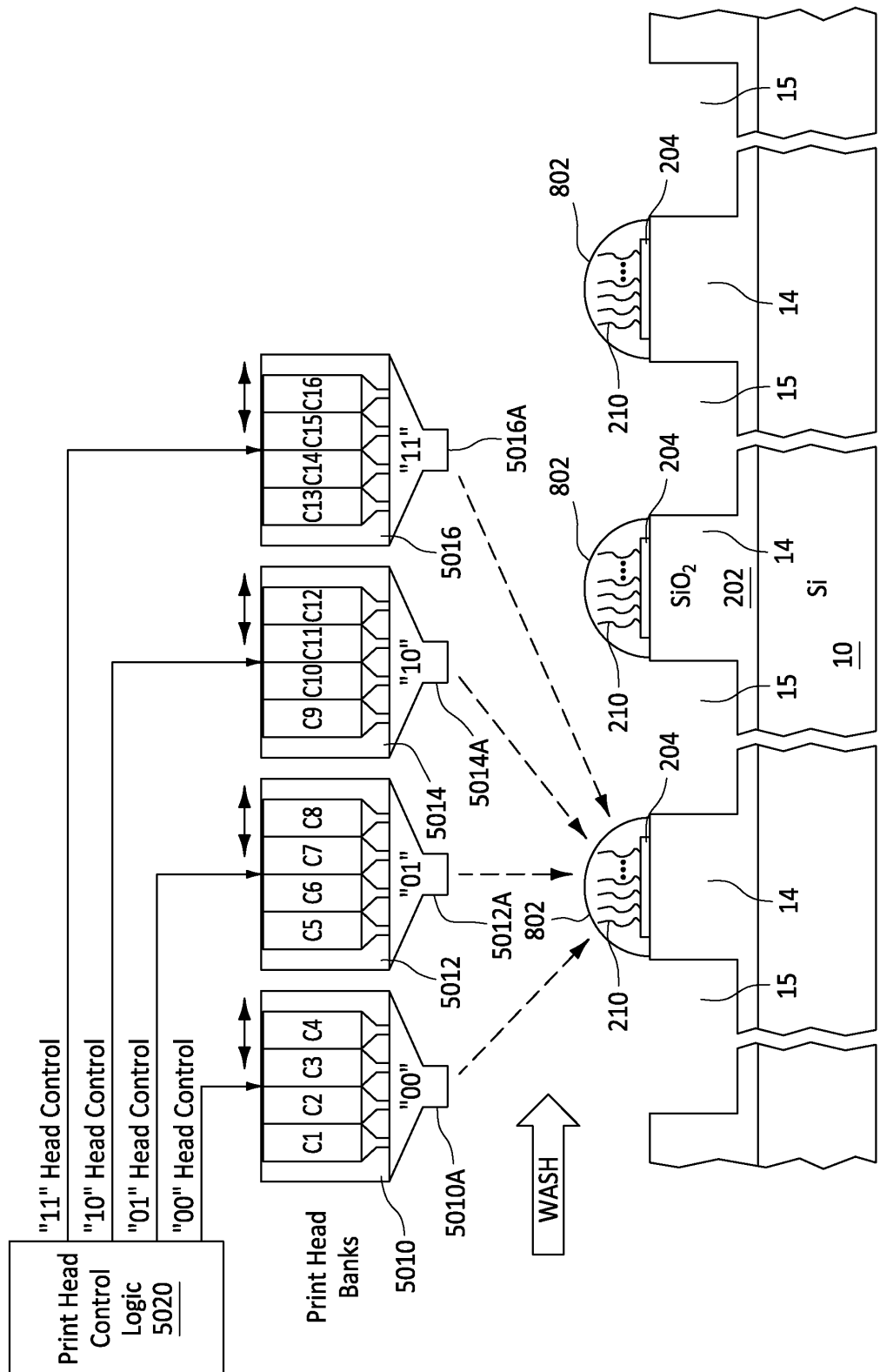


FIG. 49



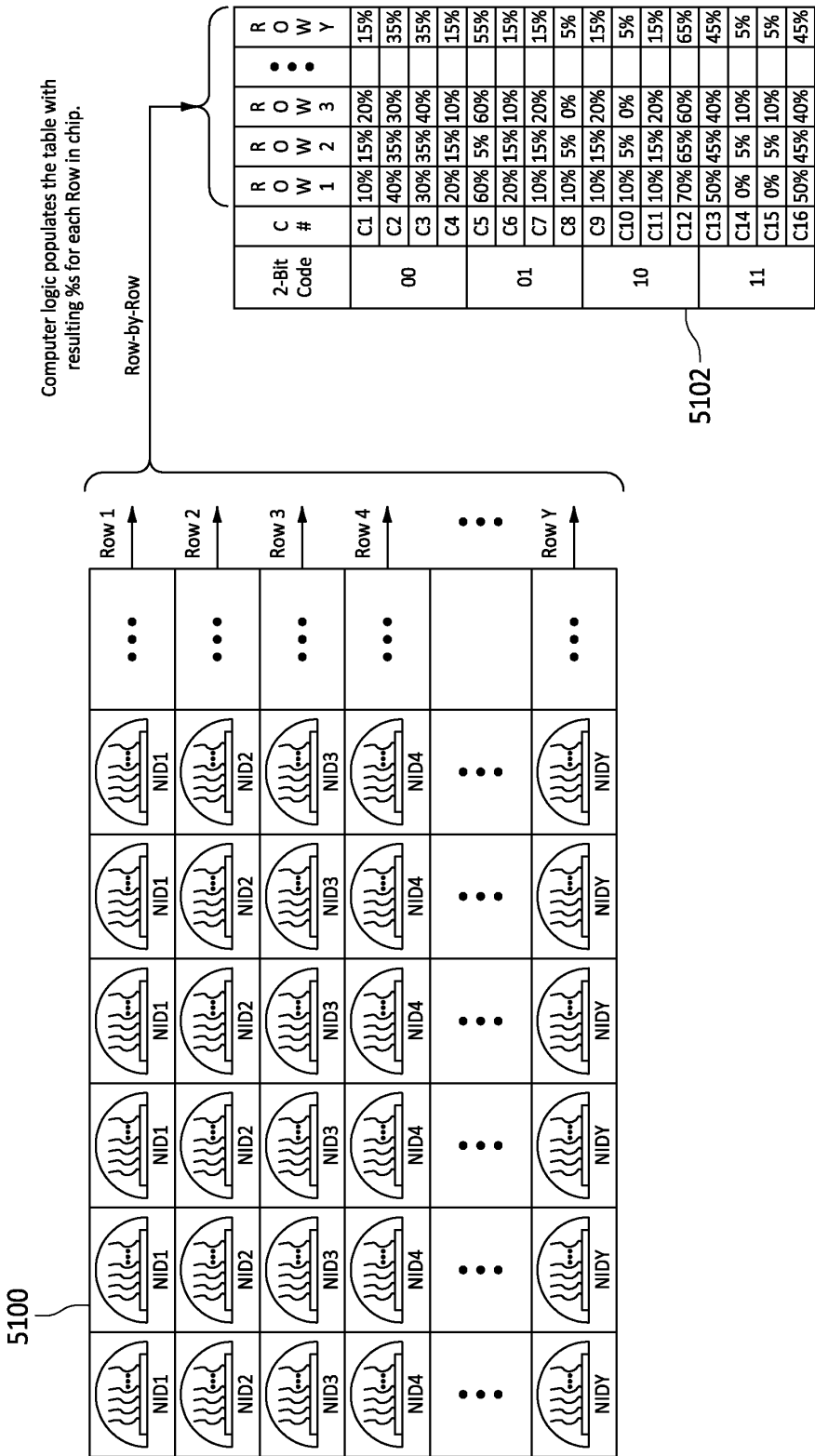


FIG. 51A

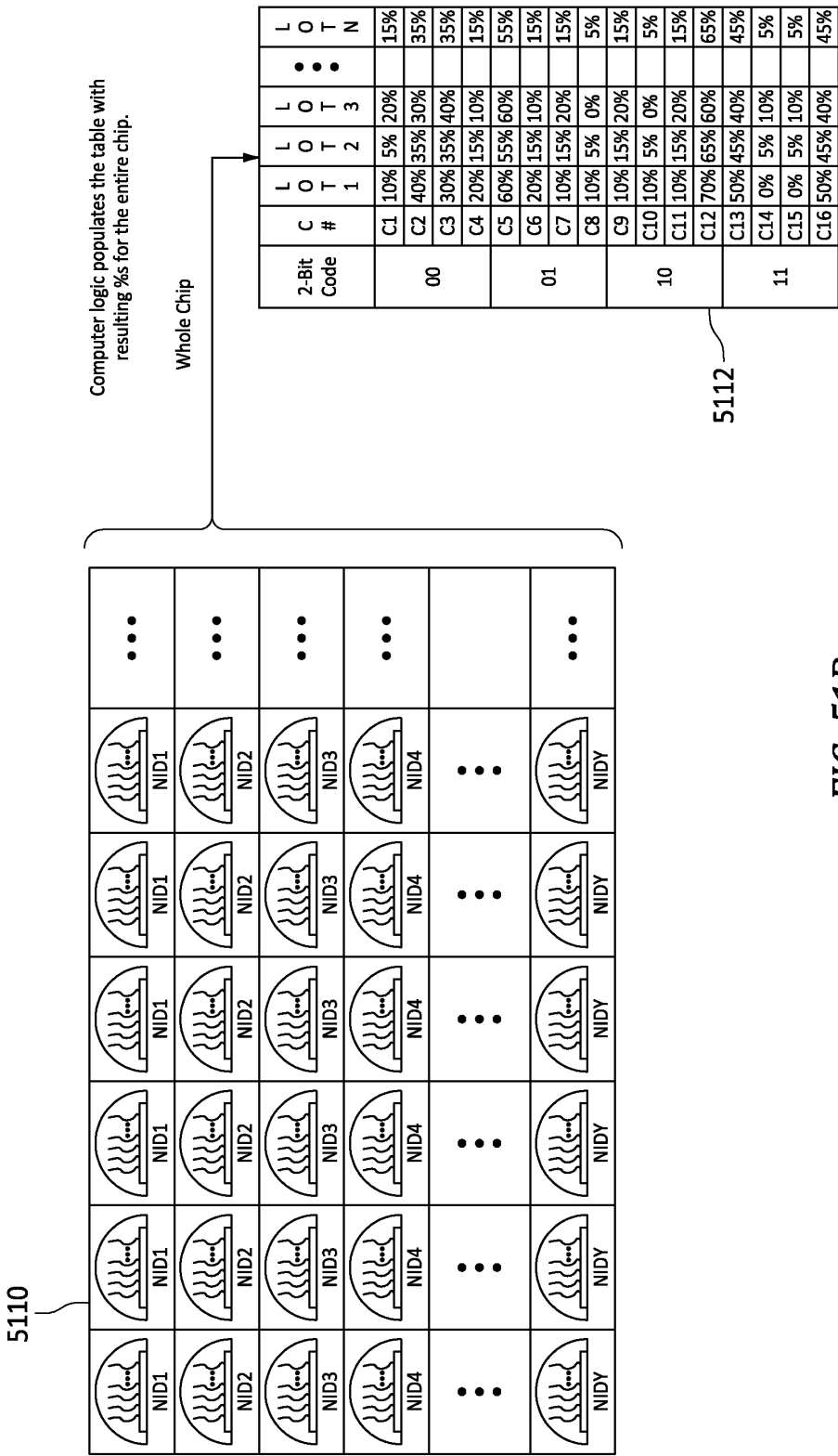
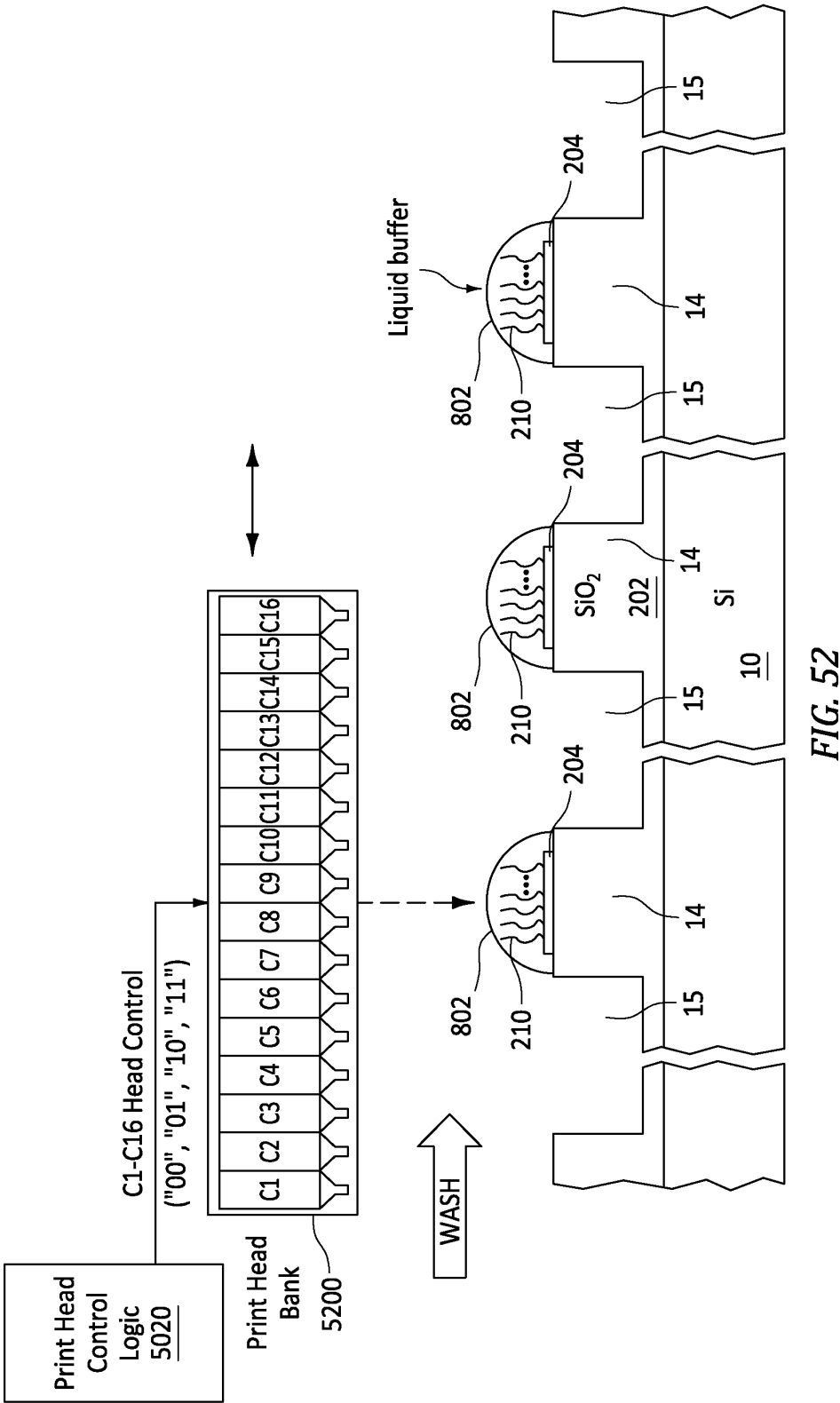


FIG. 51B



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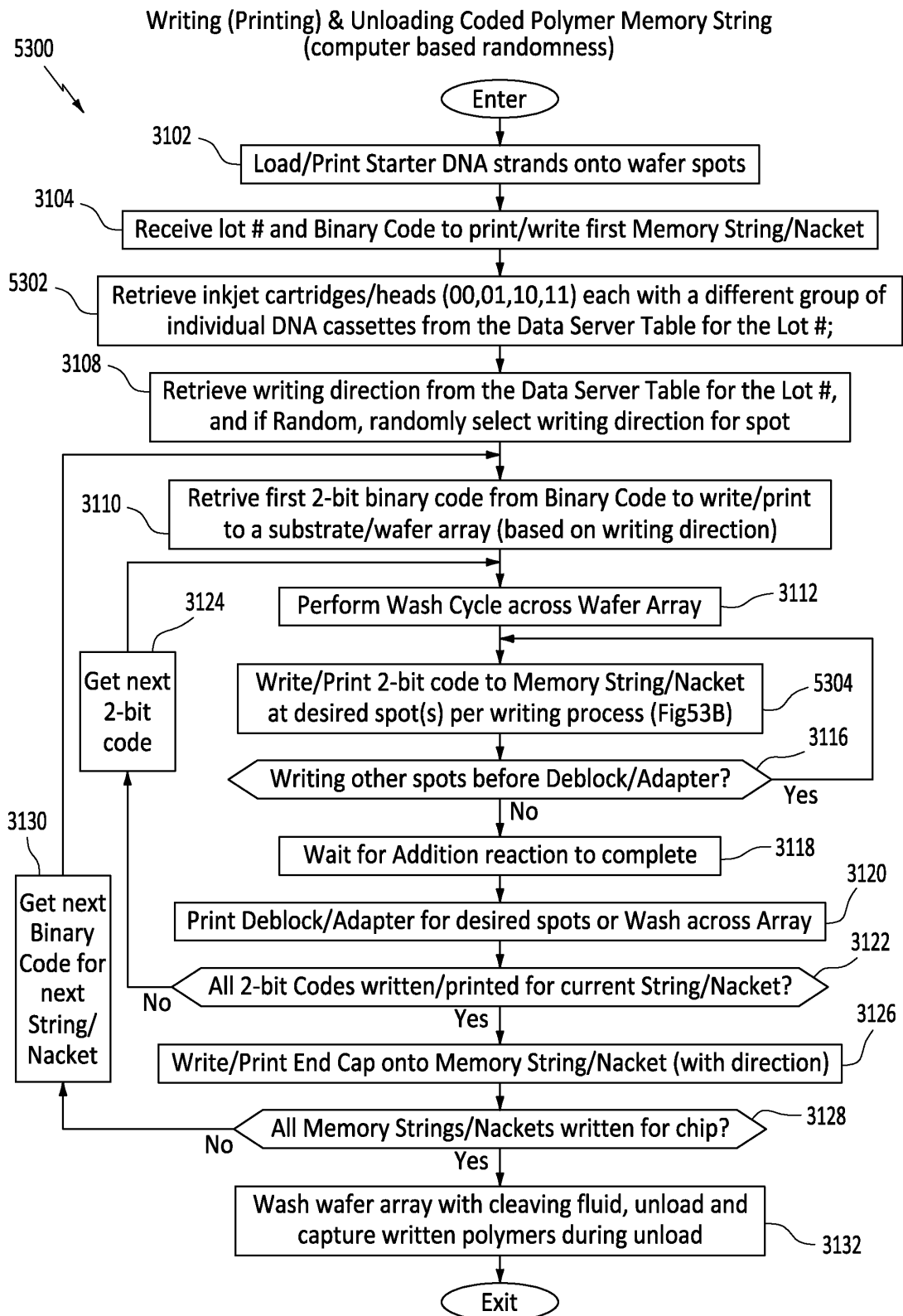


FIG. 53A

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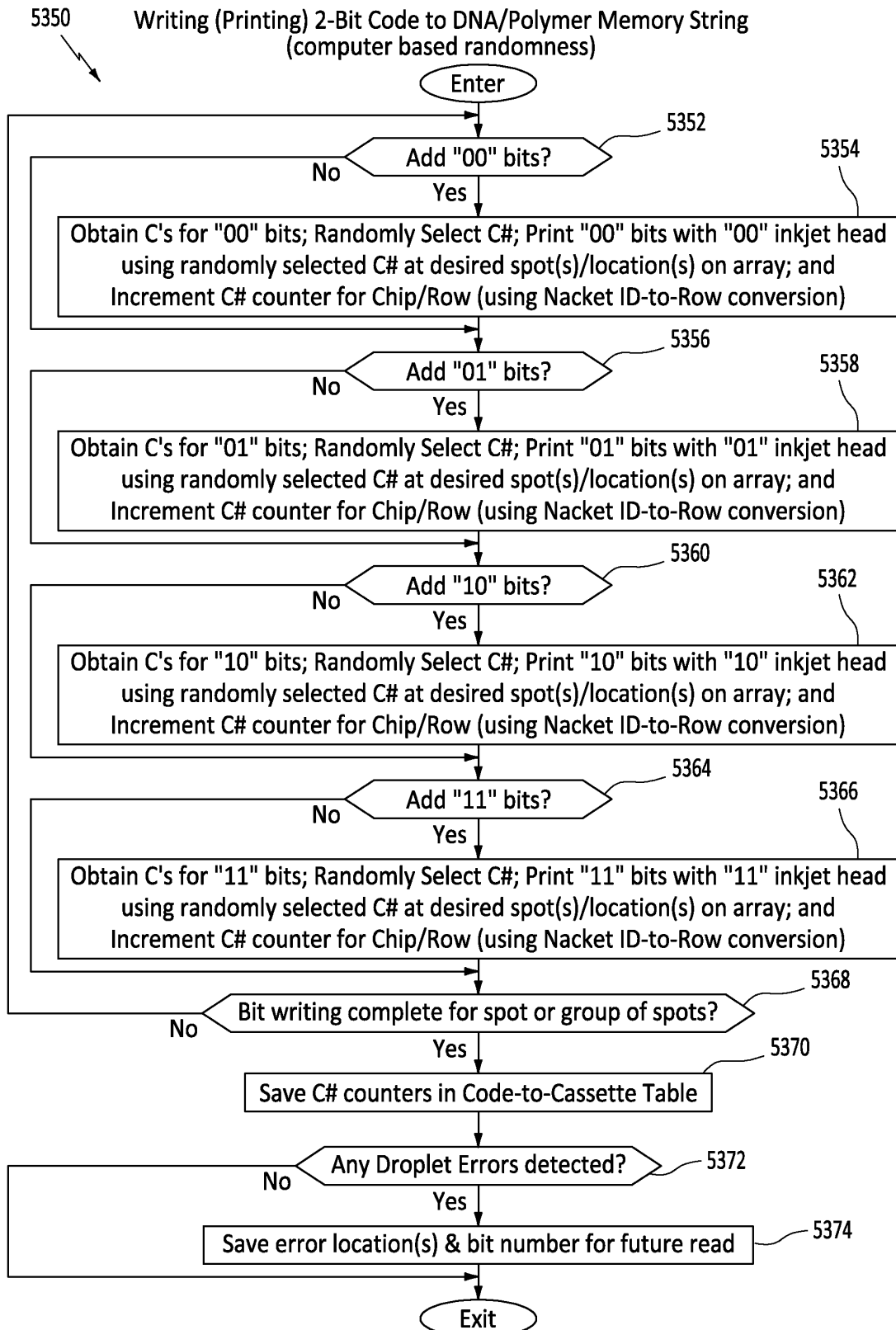


FIG. 53B

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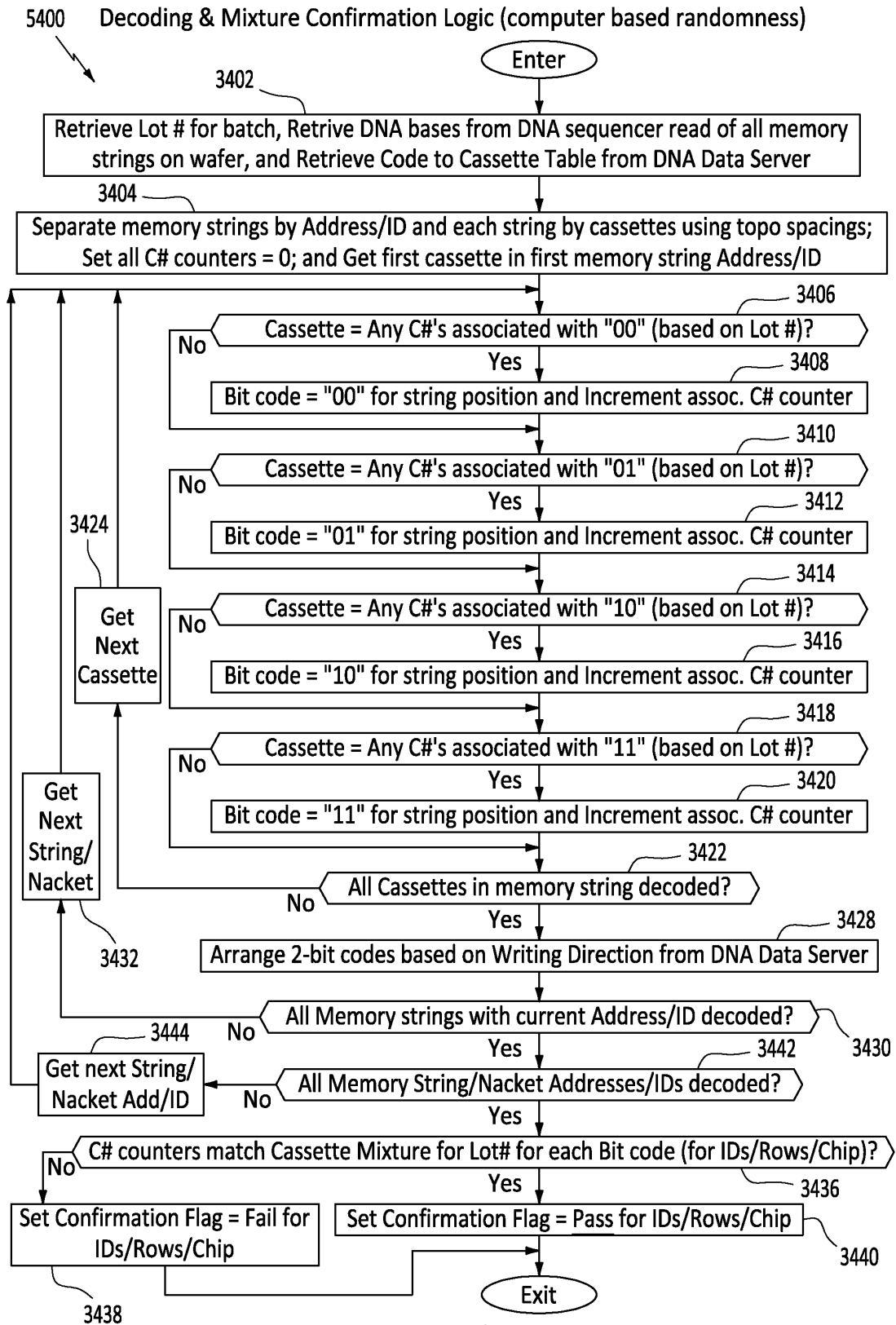


FIG. 54