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Taxonomy Proposal for Research on Reversible Logic

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Abstract*: *Reversible Logic has become a topic of interest among global researchers for its heat arresting attribute, the very reason for which CMOS devices are witnessing performance thresholds. Within a decade of substantial growth, reversible logic is quoted as one of the valued emerging technologies. The growth of research in this domain has exhibited enormous volumes of research publications. Searching the perfect published article of interest among the plethora of publications demand an enormous amount of literature study and hence is highly time-consuming. After accessing a substantial amount of articles, only a very few tend to address our needs. Hence, we propose a taxonomy for research on reversible logic in this paper which concentrates articles of relevant/similar nature into nodes so that researchers can get a first-hand reference for their choice of interest. Knowledge of pre-requisites for gaining insights into a particular domain also mandates a thorough amount of literature survey. Our taxonomy takes care of those issues by concentrating the nodes into a tree-like structure thereby providing the pre-requisite (parent node) for the node of interest (child node). For generating the taxonomy, we have used the Cosine Similarity function for measuring the distance between two author keywords. The taxonomy proposal in this paper will serve upcoming researchers in getting references for their choice of the domain rather than a comprehensive survey of the higher magnitude of published data. Researchers pursuing research in a certain domain too will benefit from the taxonomy.

Keywords: Taxonomy, Reversible Logic, Emerging Technology, Author Keywords, Cosine Similarity Function.

I. INTRODUCTION

Reversible circuits are often referred to as deterministic state machines since the pre-operation state can be uniquely determined by the post-operation state vectors. This attribute of reversible functions generated massive research in the search for a viable alternative to CMOS as the latter has started witnessing physical threshold limits due to the tremendous amount of heat generation owing to change in entropy and energy-heat converting Boolean circuits [1].

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This attribute has placed Reversible Logic as one of the most valued emerging technologies in tune with Data Mining [2], Machine Learning [3], and Blockchain [4], to name a few.

The rise in global research in reversible logic provided new researchers with a massive wealth of research articles on the web to explore, thus often confusing as to the actual trend in research sub-domains of reversible logic. Researchers have to explore an immense amount of literary articles for concluding on the required set of publications. The work in this paper compiles a whole lot of published literature into certain nodes of relevance and generates a parent-child relationship among the nodes. This approach helps the researcher to concentrate on a certain node of interest rather than conducting a huge literature survey. The study intends to provide new as well as existing researchers with related published articles in a certain sub-domain of the complete domain of reversible logic through taxonomy.

Generation of taxonomy mandates recognition of a vocabulary of study at the onset [5]. There are several online databases that can serve as the vocabulary. Readers are directed to [6] [7] for getting a first-hand glimpse of taxonomy generation. We have acknowledged IEEE Xplore as the desired vocabulary. We extracted publications related to the domain using 'Reversible Logic' as the seed term. A total of 1071 articles were fetched comprising of different types as stated in Table 1. We have concentrated on the journal articles only as journals reflect more accurate research and also provide the current trend. Out of the 120 journal articles, finally, 109 articles were of importance after removing redundancies. These 109 articles form the basis of the taxonomy presented in this paper.

Table I: Types of articles fetched from IEEE Xplore

Article Type	Article Count	Article Type	Article Count
Conferences	929	Courses	1
Journals	120	Books	5
Magazines	8	Standards	3
Early Access Articles	5		

The rest of the paper is organized as follows. The next section highlights the related work. The subsequent section concentrates on the taxonomy generation process followed by the taxonomy analysis and conclusion.

II. RELATED WORK

Early taxonomy systems lacked information retrieval features as has been pointed out in [8].

They provided the readers with only the facts.

With advancement of technology it is possible in recent times to generate more robust and relevant taxonomies; an approach targeted in this submission. The term taxonomy is often associated with zoology and biology [9] [10]. We propose taxonomy for technical research domains. We have used Cosine Similarity function to generate the taxonomy. The Cosine Similarity function is presented in Equation 2. The distance between two author keywords in different literature forms a relation between them. The details will be subsequently discussed in the following section.

$$Cosine\ Similarity = \frac{n_{x,y}}{\sqrt{n_x}\sqrt{n_y}} \quad (1)$$

Where $n_{x,y}$ = Number of articles containing both term 'x' and term 'y',

n_x = Number of articles containing only term 'x', and

n_y = Number of articles containing only term 'y'.

Apart from Cosine Similarity Function (CSF), Google Similarity Distance (GSD) [11] can also be used to calculate the distance between two vectors. GSD generates the distance matrix by calculating the hit count due to a specific search. Since, our algorithm works offline, hence online search is nit required; therefore we use CSF for our purpose.

Morrison and Ranganathan have provided a taxonomy for reversible logic/arithmetic gates in Fig 2.1 of [12] in contrast to our study which provides a comprehensive taxonomy over the whole research domain of reversible logic. On the other hand, Saeedi and Markov [13] have provided a comprehensive survey of reversible logic synthesis and optimizing algorithms until 2013. Sultana et al. [14] have presented a comprehensive survey of four variable reversible gates. Hence, after finalizing on a node and getting the list of published articles using our taxonomy, a reader can refer [13] [14] to get a preliminary notion of the research in those nodes and then proceed with a complete exploration of the relevant articles to generate an inclusive knowledge. Recent taxonomy proposals in technical domain can be found in [6] [7] where published literature has been grouped into decimal arithmetic architectures and IoT based Home Automation.

The next section provides with the details for the taxonomy generation for Reversible Logic research.

III. TAXONOMY GENERATION PROCESS

Survey and relevant taxonomy generation requires a broad collection of research articles referred to as *raw data* in purview of taxonomy. As mentioned earlier, we have used *IEEE Xplore* as the vocabulary and the *raw data* has been generated using the *seed term* "Reversible Logic". The *seed term* extracts articles from the massive online database relevant to reversible logic. The *raw data* was then segregated to shortlist only the journal publications and provided with a Document Id according to Equation 2. Hence, the final *raw data* comprised of 109 journal articles from year 1956 to year 2018 as shown in Table II. Fig. 1 provides the journal count year wise taken from Table II and presents the growth of research on Reversible Logic in terms of journal publications. Form Fig. 1 it can be concluded that the research has grown steadily over the years.

$$PID_i = [15] \rightarrow i \ \forall \ i \in [1,109] \quad (2)$$

Table II: Year wise published literature count

Year	Journals	Year	Journals	Year	Journals
1956	2	1991	1	2008	5
1958	1	1993	1	2009	2
1960	1	1996	1	2010	5
1962	1	1998	3	2011	5
1963	1	1999	4	2012	3
1965	1	2000	2	2013	4
1966	1	2001	1	2014	7
1969	1	2002	1	2015	8
1973	1	2003	3	2016	8
1974	1	2004	2	2017	4
1978	1	2005	4	2018	9
1984	1	2006	4		
1987	1	2007	3		

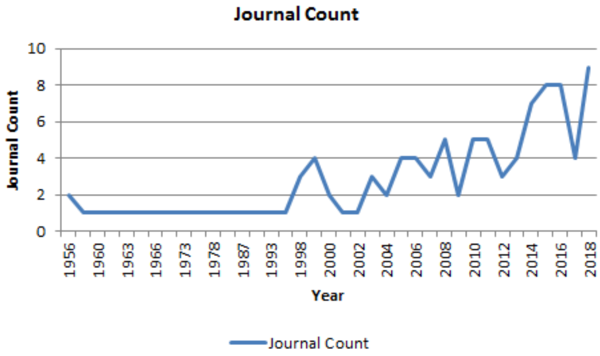

Fig. 1.Growth of research year wise

The previous step mainly concentrated on article classification as reflected in Table II. The next sub-section presents the next process of taxonomy generation.

The taxonomy has been generated using both software and manual efforts. The programming language used for the software part is Python3.7 on Intel Core i5 machine having 8 GB DDR2 memory.

A. Generation of 'Keyword' and 'Abstract' database

In this step, two databases have been generated. Initially the file downloaded from IEEE was renamed as 'exportfile'. File 'metadata' was generated from 'exportfile'. The attributes of 'metadata' are PID, Document Title, Authors, Year, Abstract and Author Keyword. The attribute PID was appended to the database to refer to a unique publication according to Equation 2. From 'metadata', two databases were generated named 'keyword' and 'abstract' having the attributes 'Keywords' and {PID, Abstract} respectively. The 'keyword' database contains all the 221 unique author keywords present in the comprehensive literature. This whole process was automated using software programs.

B. Generation of 'index' database

The 'index' database was generated using software from the 'keyword' and the 'abstract' databases. The attributes in the 'index' database are as follows: Author Keywords, PIDs, and Frequency. Author Keywords relate to the unique 221 entries in the 'keyword' database. These author keywords from the 'keyword' database were searched in the abstracts in the 'abstract' database and the frequency of occurrences were noted in the 'index' database. It is to be noted that presence of a certain Author Keyword in an abstract accounted for a frequency count of 'one' in-spite of having multiple occurrences in that abstract.

After generating the 'index' database, it was observed that there were multiple Author Keywords having identical meanings. Hence these keywords were clubbed into unique texts. Table III presents the unique terms and the respective Author Keywords. This was a manual process. A total of 221 Author Keywords post clubbing exhibited only 12 unique texts. These texts formed the nodes of the taxonomy that is under consideration. Hence the taxonomy proposal reflects the research on reversible logic till date to be concentrated among 12 unique terms/nodes.

The 'index' database was then sorted in a decreasing order of frequency count placing the term having the highest frequency count as the first tuple in the database. This forms the root node in the taxonomy as this node has been found in the highest number of publications. These unique terms were then assigned a unique identifier TNi; TN = taxonomy Node.

Table III: Unique texts representing multiple Author Keywords

Taxonomy Node	Author Keywords
Reversible Logic	logic reversible logic adiabatic logic adiabatic computing reversibility reversible computing conservative logic logic design reversible logic synthesis reversible network reversible lanes reversible data hiding logic synthesis
Quantum Computing	quantum computing cellular automata quantum circuits quantum circuit quantum computation quantumdot quantumdot cellular automata qudits entanglement
Digital Circuits	reversible circuits reversible circuit sequential circuits integrated circuits circuit synthesis synchronous sequential circuit minimal garbage garbage garbage outputs testing registers full adder counters minimization lookahead flipflop postsynthesis optimization ring oscillator ro
Gates	toffoli gate fredkin gate toffoli gates quantum gates swap gates gate sinking negative control paritypreserving
Emerging Technologies	optical computing cryptography emerging technologies nanotechnology image encryption nanocomputing
	serpent cipher image encryption
Design	boolean functions reliability threshold voltage satisfiability decision diagrams energy efficiency fault coverage nearest neighbor fault diagnosis test generation failure physical analysis supercapacitors
Power	low power differential power analysis power amplifier low power dissipation power analysis attack power distribution
Miscellaneous	transform silicon atpg microring resonators onoff ratio sidechannel attacks nems fault coverage ctestable thinfilm transistors fault diagnosis test generation plasma oxidation resistive switching serpent cipher bias temperature instability bti memory cellular automata operational procedures radar inalngan robot skin

Table IV provides all the taxonomy nodes with respective taxonomy IDs, and Frequency Count..

Table IV: Taxonomy nodes and IDs

Taxonomy Node ID	Node	Frequency
TN1	Reversible Logic	70
TN2	Digital Circuits	44
TN3	Quantum Comp	29
TN4	Gates	22
TN5	Miscellaneous	22
TN6	Design	21
TN7	Emerging Tech	17
TN8	Algorithm	15
TN9	Power	12
TN10	Complexity	11
TN11	Memory	10
TN12	Security	6

The comprehensive published literature concentrates on the 12 taxonomy nodes presented in Table IV. Table V presents the PIDs (paper IDs) associated with each taxonomy node.

Table V: Taxonomy nodes vs. PIDs

Taxonomy Node	PIDs
Reversible Logic	PID1;PID2;PID3;PID4;PID5;PID6;PID7;PID9;PID10;PID11;PID12;PID13;PID14;PID15;PID16;PID17;PID18;PID19;PID20;PID21;PID22;PID23;PID24;PID25;PID27;PID28;PID29;PID30;PID33;PID34;PID35;PID36;PID37;PID42;PID43;PID44;PID45;PID46;PID48;PID49;PID50;PID51;PID53;PID54;PID56;PID57;PID58;PID60;PID65;PID66;PID72;PID73;PID76;PID83;PID84;PID88;PID89;PID91;PID92;PID96;PID99;PID100;PID108;PID109;PID38;PID67;PID55;PID40;PID47;PID63
Gates	PID6;PID22;PID36;PID45;PID50;PID53;PID64;PID68;PID3;PID13;PID16;PID33;PID28;PID30;PID31;PID66;PID41;PID70;PID40;PID69;PID34;PID106
Security	PID14;PID15;PID63;PID65;PID74;PID97
Memory	PID13;PID26;PID55;PID65;PID73;PID78;PID79;PID85;PID88;PID94
Digital Circuits	PID3;PID8;PID12;PID16;PID26;PID27;PID31;PID33;PID41;PID51;PID53;PID54;PID67;PID70;PID11;PID28;PID29;PID32;PID34;PID61;PID66;PID10;PID13;PID58;PID85;PID7;PID18;PID23;PID35;PID38;PID37;PID73;PID79;PID87;PID89;PID99;PID9;PID56;PID90;PID14;PID39;PID22;PID69;PID97
Quantum Comp	PID6;PID12;PID22;PID26;PID31;PID34;PID45;PID48;PID61;PID68;PID3;PID13;PID23;PID37;PID38;PID55;PID74;PID78;PID28;PID41;PID69;PID70;PID103;PID36;PID64;PID51;PID67;PID89;PID77
Miscellaneous	PID30;PID39;PID103;PID5;PID104;PID70;PID87;PID40;PID42;PID73;PID15;PID25;PID13;PID36;PID79;PID32;PID74;PID75;PID78;PID76;PID106;PID107
Design	PID14;PID18;PID28;PID38;PID44;PID32;PID37;PID65;PID79;PID99;PID75;PID106;PID48;PID70;PID87;PID104;PID24;PID47;PID69;PID97;PID98
Emerging Tech	PID22;PID48;PID50;PID31;PID65;PID67;PID45;PID69;PID3;PID76;PID23;PID16;PID24;PID14;PID26;PID59;PID78
Algorithm	PID6;PID14;PID16;PID22;PID30;PID31;PID35;PID45;PID53;PID60;PID66;PID67;PID78;PID87;PID89
Power	PID14;PID22;PID25;PID32;PID35;PID55;PID57;PID74;PID15;PID104;PID105;PID98
Complexity	PID13;PID19;PID26;PID32;PID33;PID45;PID50;PID53;PID63;PID74;PID89

Table V serves the purpose for the researchers in getting the first-hand reference to publications according to their choice of interest.

C. Generation of Matrices for Equation 1

This step generates the matrices for generating the taxonomy. As discussed earlier, Cosine Similarity Function presented in Equation 1 has been used to generate the distance between two Author Keywords. The inter-nodal relationship between two taxonomy nodes is decided by the value of the Cosine Similarity Function. Hence, if the angle between two nodes is '0', then $\cos 0 = 1 \Rightarrow$ exactly similar, and if the nodes are orthogonal, then $\cos 90 = 0 \Rightarrow$ completely dissimilar. Hence, the values range between o and 1 for all the combinations. The numerator and denominator of Equation are provided in Table VI and Table VII respectively.

Table VI: Term Co-occurrence Matrix (Distance between two terms - $n_{x,y}$)

R/C	TN1	TN2	TN3	TN4	TN5	TN6	TN7	TN8	TN9	TN10	TN11	TN12
TN1	-	30	17	15	10	11	12	12	7	8	5	4
TN2	30	-	18	13	7	12	9	10	4	6	5	2
TN3	17	18	-	14	6	6	10	7	3	5	4	1
TN4	15	13	14	-	6	4	7	8	1	5	1	0
TN5	10	7	6	6	-	7	2	3	5	3	4	2
TN6	11	12	6	4	7	-	5	2	4	1	2	3
TN7	12	9	10	7	2	5	-	7	2	3	3	2
TN8	12	10	7	8	3	2	7	-	3	3	1	1
TN9	7	4	3	1	5	4	2	3	-	2	1	3
TN10	8	6	5	5	3	1	3	3	2	-	2	2
TN11	5	5	4	1	4	2	3	1	1	2	-	1
TN12	4	2	1	0	2	3	2	1	3	2	1	-

Table VII: Matrix for the $\sqrt{n_x}\sqrt{n_y}$ term

R/C	TN1	TN2	TN3	TN4	TN5	TN6	TN7	TN8	TN9	TN10	TN11	TN12
TN1	-	55.5	45.06	39.24	39.24	38.34	34.5	32.4	28.98	27.75	26.46	20.49
TN2	55.5	-	35.72	31.11	31.11	30.4	27.35	25.69	22.98	22	20.98	16.25
TN3	45.06	35.72	-	25.26	25.26	24.68	22.2	20.86	18.65	17.86	17.03	13.19
TN4	39.24	31.11	25.26	-	22	21.49	19.34	18.17	16.25	15.56	14.83	11.49
TN5	39.24	31.11	25.26	22	-	21.49	19.34	18.17	16.25	15.56	14.83	11.49
TN6	38.34	30.4	24.68	21.49	21.49	-	18.89	17.75	15.87	15.2	14.49	11.22
TN7	34.5	27.35	22.2	19.34	19.34	18.89	-	15.97	14.28	13.67	13.04	10.1
TN8	32.4	25.69	20.86	18.17	18.17	17.75	15.97	-	13.42	12.85	12.25	9.49
TN9	28.98	22.98	18.65	16.25	16.25	15.87	14.28	13.42	-	11.49	10.95	8.49
TN10	27.75	22	17.86	15.56	15.56	15.2	13.67	12.85	11.49	-	10.49	8.12
TN11	26.46	20.98	17.03	14.83	14.83	14.49	13.04	12.25	10.95	10.49	-	7.75
TN12	20.49	16.25	13.19	11.49	11.49	11.22	10.1	9.49	8.49	8.12	7.75	-

Table VIII: Cosine Similarity Index Matrix

R/C	TN1	TN2	TN3	TN4	TN5	TN6	TN7	TN8	TN9	TN10	TN11	TN12
TN1	-	0.54	0.38	0.38	0.25	0.29	0.35	0.37	0.24	0.29	0.19	0.2
TN2	0.54	-	0.5	0.42	0.23	0.39	0.33	0.39	0.17	0.27	0.24	0.12
TN3	0.38	0.5	-	0.55	0.24	0.24	0.45	0.34	0.16	0.28	0.23	0.08
TN4	0.38	0.42	0.55	-	0.27	0.19	0.36	0.44	0.06	0.32	0.07	0

TN5	0.25	0.23	0.24	0.27	-	0.33	0.1	0.17	0.31	0.19	0.27	0.17
TN6	0.29	0.39	0.24	0.19	0.33	-	0.26	0.11	0.25	0.07	0.14	0.27
TN7	0.35	0.33	0.45	0.36	0.1	0.26	-	0.44	0.14	0.22	0.23	0.2
TN8	0.37	0.39	0.34	0.44	0.17	0.11	0.44	-	0.22	0.23	0.08	0.11
TN9	0.24	0.17	0.16	0.06	0.31	0.25	0.14	0.22	-	0.17	0.09	0.35
TN10	0.29	0.27	0.28	0.32	0.19	0.07	0.22	0.23	0.17	-	0.19	0.25
TN11	0.19	0.24	0.23	0.07	0.27	0.14	0.23	0.08	0.09	0.19	-	0.13
TN12	0.2	0.12	0.08	0	0.17	0.27	0.2	0.11	0.35	0.25	0.13	-

As discussed earlier, Table VI and Table VII are automated processes. Using Table VI and Table VII, the final Cosine Similarity Index was generated in Table VIII which serves as the basic for the taxonomy generation.

D. Generation of Taxonomy

The taxonomy is generated by horizontally scanning each row of Table VIII.

Let i denote the row index and j denote the column index. For each TN_i in each row, the column with the maximum value is noted. The TN_j hence becomes the parent of TN_i if not considered earlier while calculating for TN_j.

The pseudo code for taxonomy generation is as follows:

```
Begin:
for i ∈ [1, 12]
for j ∈ [1, 12]
    scan R[i]C[j] for the highest value ∀ i ≠ x ∩ j ≠ y
x = i for highest R[i]C[j]
y = j for highest R[i]C[j]
if (TN[y] is not related to TN[x] previously)
    TN[x] is the child of TN[y]
else
    goto L2
End
```

Where i, j denote the row and column indices respectively.

Table IX presents the parent child relationship after complete scan of Table VIII. Any parent which does not have any child is considered as the leaf node.

Table IX: Parent Child Relationship

Parent	Child	Parent	Child
TN1	TN2	TN7	Leaf Node
TN2	TN6, TN11	TN8	TN4
TN3	TN7	TN9	TN12
TN4	TN3, TN10	TN10	Leaf Node
TN5	Leaf Node	TN11	Leaf Node
TN6	TN5, TN9	TN12	Leaf Node

Putting the data in Table IX in taxonomical relationship generates the following hierarchy.

1 TN1
1.1 TN2
1.1.1 TN6
1.1.1.1 TN5
1.1.1.2 TN9
1.1.1.2.1 TN12
1.1.2 TN11
1.2 TN8
1.2.1 TN4
1.2.1.1 TN3
1.2.1.1.1 TN7
1.2.1.2 TN10

Replacing the taxonomy node IDs by their taxonomy terms generate the following.

1 Reversible Logic
1.1 Digital Circuits
1.1.1 Design
1.1.1.1 Miscellaneous
1.1.1.2 Power
1.1.1.2.1 Security
1.1.2 Memory
1.2 Algorithm
1.2.1 Gates
1.2.1.1 Quantum Computing
1.2.1.1.1 Emerging Technologies
1.2.1.2 Complexity

Figure 2 represents the above hierarchy as a schematic.

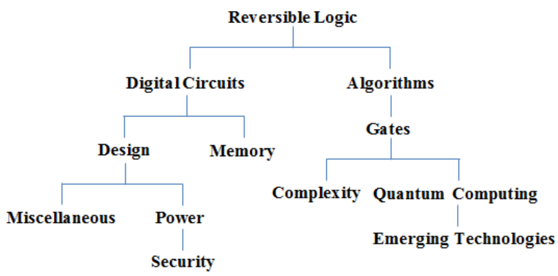

Fig. 2.Taxonomy for Research on Reversible Logic

From Figure 2, it can be concluded that the domain of Reversible Logic has witnessed research in primarily two sub-domains – Digital Circuits, and Algorithms; both contributing the major share in published literature (frequency of 44 and 29 respectively). Research on Digital Circuits also has been concentrated on Design issues and Memory.

IV. CONCLUSION

This communication proposes taxonomy on research on Reversible Logic. The major motivation behind this work is to reduce the time consumed during the literature study and also to cluster similar research into relevant nodes so that a researcher gets a first-hand reference of the literature of interest. The work can be further extended to incorporate other online databases to expand the current vocabulary. Other taxonomy generation algorithms can also be explored to compare the presented taxonomy with future taxonomies to furnish a more robust taxonomy. The taxonomy also reflects that the domain of Reversible Logic is presently one of the most appreciated emerging technologies.

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