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INTEGRATED CIRCUIT DESIGN RESEARCH RANKING FOR WORLDWIDE UNIVERSITIES

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The proliferation of integrated circuits (ICs) in the present technological era has brought forth revolutionary digital modernization that has ultimately transformed the history and lifestyle of humankind. ICs have become the heart of practically all state-of-the-art electronic devices such as computers, cell phones, video game consoles, and cameras. This ever-flourishing IC design industry is knowledge-intensive, which in turn translates into a huge appetite for technically precocious talents. Hence, in an effort to fuel and further foster the industry with more highly skilled manpower and at the same time to vie for a share of the burgeoning industry, higher educational institutions and universities from all around the globe are placing greater than ever emphasis on IC design research. Most importantly, strenuous efforts in a holistic manner are being made by each university in order to elicit outstanding and top-notch research in IC design. The authors have conducted a detailed and extensive survey to rank the various universities of the world in the field of IC design based on their research performance. In fact, assessments in the form of ranking have gained prominence over the recent years captivating the attention of a large number of students and universities. It helps the students in knowing how each university is progressing in a particular field and in turn helps the universities in analyzing their positions globally to remain competitive. Three ranking indicators, namely the *Number of Publications*, *Citation Counts*, and *Cites per Paper* have been chosen. The methodology used in ranking is also reported. The universities occupying the top echelons in IC design research are identified and a proven three-pronged approach for eliciting outstanding research performance is discussed.

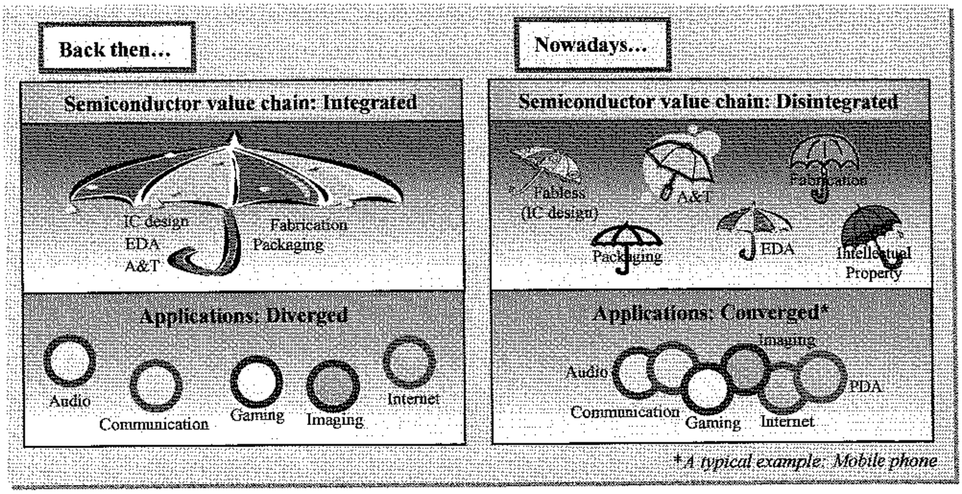
Keywords: Integrated circuit design; ranking; universities.

1. The Integrated Circuit Design Industry

Today, integrated circuit design (IC design) is of immense industrial importance. It is the backbone entity of one of the largest industries in the world, namely the semiconductor industry. Integrated circuits (ICs) are at the heart of recent developments in communication, automotive, health and safety, internet, and other numerous applications. There has been enormous development in this field since its invention and the trend is still moving ahead with great vigor. The first planar integrated circuit which was fabricated in 1961 had only two transistors and within four decades the Pentium IV processor comprised 42 million transistors by 2001.[1] Contemporary ICs are packed with more functions and are of higher levels of integration and sophistication. As of 2006, the number of transistors on a large IC may have exceeded the population of earth. This unprecedented growth was made possible by the incessant miniaturization of transistor feature sizes and its evolution has been more drastic than expected: While the Semiconductor Industry Association (SIA) predicted that the process technology by the year 2008 would be around 60 nm, Multi-National Companies (MNCs) like Intel are already venturing into volume production of 45 nm micro-architectures in mid-2007 and heading toward the 32 nm technology.[2]

However, the IC design industry is not without challenges especially as we move into the nanometer regime where conventional approaches will no longer work. Back in the 1970s,[3] the semiconductor industry adopted a business model widely known as the *vertical integration* model, whereby a diversity of business operations, namely, IC design, fabrication, Assembly & Test (A&T), packaging, Electronic Design Automation (EDA), were all integrated and came under the same umbrella. During that period of time, the application domain has been distinct and less sophisticated while the consumers paid for products that served specific functions offered by the suppliers with bare-minimum features. For example, mobile phone during that era was solely used for communication. It had no camera, audio, internet, and gaming functions. However, in recent years, the semiconductor industry has witnessed a decomposition and specialization of its value chain, into a business model known as the *vertical disintegration* model, whereby its business operations no longer come under the same umbrella.[4,5] This trend is vastly motivated by the rapid advancement of technology, the extraordinary design complexity, and the exceptionally high IC development cost. Moreover, an apparent convergence and generalization of the application domain has also been observed. The boundaries among varying application domains have become fairly vague and the consumers nowadays enjoy the most integrated solutions with wide-ranging utilities.

In summary, the semiconductor industry value chain has moved from "integrated" to "disintegrated", whereas its application domain has evolved from "diverged" to "converged", albeit not coincidentally. Figure 1 illustrates the transition by using the mobile phone as a typical example. Mobile phones in the early days were used exclusively as a communication device. Nowadays, apart from its



(a) (b)

Fig. 1. (a) Past business model. (b) Contemporary business model.

conventional use, mobile phones serve a wide range of purposes ever imaginable, e.g., as imaging device (camera/video), audio device (MP3 player), and handheld computer (Personal Digital Assistant, PDA), all of which were historically streamlined into the diverged application domains.

IC design presents an instrumental impact in boosting and strengthening the entire semiconductor ecosystem. It has become increasingly sophisticated and challenging, which serves as one of the motivating factors gearing the semiconductor value chain into disintegration of its business entities. Joint efforts in IC design research by companies and universities alike are, therefore, required to explore more intuitive ways to sustain and prolong the industry's historic growth track. By spinning off the capital-intensive segment or by being fabless even during its inception, the pure-play IC design houses can potentially generate greater revenue by venturing and focusing more on IC design. IC design companies are talent intensive instead of labor intensive, hence accentuating the need for more well-educated design talents to nourish fabless companies with a continual stream of technical prowess. This has vaulted to the forefront attention of both industry and academics.

2. Motivation of the Work

Numerous universities from all around the world are already laying significant emphasis on the research of IC design, with each university striving to outperform its counterparts in order to clinch the top notch in this field. Hence, being armed with the knowledge of how each institution fares against its counterparts will be a good tool toward achieving its objectives. Therefore, it is important to assess the research performance of these worldwide universities in the specific field of IC design.

The assessment, which is usually carried out in the form of ranking,[6] helps researchers and prospective students in knowing how each university is progressing in this particular field, and in turn assists them to determine the institution of their choice, be it for work or study. Moreover, ranking brings awareness. The survey results also help the universities to be aware of their rankings from a global perspective. Furthermore, it will also be of great interest to personnel in the industry, e.g., IC designers, engineers, managers, and recruiters to hire potential employees with high caliber. As for investors or venture capitalists, the ranking results can help them in making timely and informed business decision to increase the confidence level of garnering high Return-On-Investment (ROI).

In fact, worldwide universities ranking, such as that conducted by The Times Higher Educational Supplement (THES)[7–9] have gained prominence over the recent years and captivated the attention of a large number of students and universities. Moreover, rankings and surveys with respect to a particular field of specialization such as computing and software engineering, which are normally confined within a specific geographical region, e.g., the United States, are also readily available in the literature.[10] Nonetheless, based on our extensive research and to the best of our knowledge, we have found a hitherto vacuum of such rankings in the specialized field of IC design, despite it being one of the hottest revenue-making industries. Hence, to address this scarcity, we have conducted a detailed and exhaustive survey to rank the various universities of the world in the field of IC design based on their journal publications in the past ten years (1997–2006).

Three ranking indicators, namely the *Number of Publications*, *Citation Counts*, and *Cites per Paper* have been chosen as the yardsticks for comparison among different universities. The methodology used in the ranking is also elaborated. More than 200 educational institutions have been meticulously scanned for articles, letters, reviews, and corrections. Ultimately, the universities occupying the top echelons in IC design research are identified. For conciseness, we have extracted *the top 40 universities* and grouped them into bands according to the scores for each criterion over a period of ten years, i.e., from 1997 to 2006. Interesting statistics, results, findings and discussions covering the Who's Who (top performers) in the specific IC design fields of Analog, Digital, and Radio Frequency (RF) are also reported.

3. Methodology

Three ranking indicators are used to reveal prowess in IC design research: (1) *Number of Publications*, which gives the total number of papers published by each university, (2) *Citation Counts*, which denotes the number of times the papers published have been cited, and (3) *Cites per Paper*, which tracks the average citations for an individual paper, and is given in Eq. (1)

$$Cites\ per\ Paper_i = \frac{Citation_i}{Number\ of\ Publication_i}, \tag{1}$$

where i is the ith year.

Citation analysis has been considered as it reveals the relevance and impact of the research work carried out by a university on the international research community.

3.1. *Database compilation*

The rapidly growing IC design field with broad utilities can be classified into three subcategories, namely Digital IC, Analog IC, and Radio Frequency (RF) IC. Digital ICs are vastly used in designing microprocessors, memories, Arithmetic Logic Units (ALUs), Field Programmable Gate Arrays (FPGAs), etc. Analog ICs are often used in the design of components such as operational amplifiers, oscillators, and regulators, while RF ICs are more concerned with the design of circuits for high-frequency applications such as wireless transceivers, Bluetooth, and WiFi-802.11.

Our ranking database is constructed by extracting all relevant papers from Web of Science — ISI Web of Knowledge by Thomson Scientific,[11] as it offers access to comprehensive archival research publications that are more closely related to the field of IC design. The keywords used to search the papers are "analog*", "digital*", and "radio frequency* or rf", which represent the three IC design fields. These keywords are adopted separately each time to extract the maximum number of papers. The time span has been chosen for a period of ten years, i.e., from 1997 to 2006. English is the only language chosen as it is the most widely used language in the academic world. Results obtained are further refined by selecting the subject categories and the source (journal) titles.

In the subject categories, 11 interdisciplinary fields have been chosen — Electrical and Electronic Engineering, Telecommunications, and Engineering Multidisciplinary, are some of them. These interdisciplinary fields are selected so as to embrace all possible areas in IC design. In addition, the source titles selected are prestigious journals with considerably high impact factor such as the *IEEE Transactions on Circuits and Systems*, *IEEE Journal of Solid-State Circuits*, *IEEE Transactions on Microwave Theory and Techniques*, etc. An average of 55 journal titles has been selected in each field so as to ensure complete inclusion of all IC design related publications.

3.2. *Duplicate removal*

By applying the above-mentioned systematic methodology, we collated a database of approximately 9000 records in the field of Digital IC, 3000 records in the field of Analog IC, and 5000 records in RF IC design. Extra care has been taken to eliminate the inaccuracies in the data collecting process. For instance, the database has been carefully scrutinized to filter out duplicate journal entries. This is because a publication can be counted more than once if it falls under more than one of the three IC design fields, which will in turn affect the accuracy of the ranking. These duplicates are removed using the "Endnote" software[12] to obtain a precise number of publications. Following that, simple mathematical procedures have also been adopted to calculate the *Citation Counts* in each field, for all the institutions over a ten-year period.

3.3. *Scoring procedure*

Our scoring procedure leverages from the concept of data normalization, based on the statistics obtained for each university over the past ten years for all the three IC design fields. During this period of time, a university that performs well in a certain year may not necessarily be maintaining its performances in the subsequent years. Conversely, a university that has inferior research performance in a certain year may improve tremendously in the following year. Here, we also look at the university's consistency in research performance throughout the ten-year duration. Therefore, a scoring procedure that recursively measures the contribution of the universities on a yearly basis over the ten-year time span is critical to yield meaningful ranking results as it is important for a university to be consistently productive in order to have a good ranking.

In our scoring procedure, among the top 40 institutions, the one that produces the maximum number of publications, assuming N_1, in a certain year is taken as the reference and assigned a score of 100%. Subsequently, another university that produces N_2 number of publications, where $N_2 < N_1$, will be assigned a score of $(N_2/N_1) \times 100 = N_3\%$. This computation will then be replicated for the remaining years (from 1998 to 2006). Based on the yearwise scores, an average score is then calculated for each university. The following paragraph gives a clearer explanation for the computation of the score for each university.

Table 1 shows an example of three universities, namely Univ A, Univ B, and Univ C (assuming the total number of universities under consideration is three) with their publication numbers from 1997 to 2006. Within the year of 1997, Univ A produced ten publications while Univ B and Univ C produced five publications each. Since Univ A produced the most number of publications, it is taken as the reference and thus assigned a score of 100%. The rest of the universities will be normalized with respect to the one that produced the most number of publications, namely Univ A in this case. Consequently, Univ B and Univ C will be assigned a score of $(50/100) \times 100 = 50\%$. Proceeding in a similar manner from 1998 to 2006, the score for each university is computed. The average score is then computed by dividing the total score by the number of years within the timeframe of consideration, i.e., ten in this case. The same procedure has been adopted for the other two ranking indicators, namely *Citation Counts* and *Cites per Paper*.

Table 1. An example showing the scoring procedure.

	Number of publications			Score (%)		
Year	Univ A	Univ B	Univ C	Univ A	Univ B	Univ C
1997	10	5	5	100	50	50
1998	8	3	5	100	37.5	62.5
1999	12	6	9	100	50	75
2000	7	10	11	63.6	90.9	100
2001	18	15	9	100	83.3	50
2002	16	15	17	94.1	88.2	100
2003	19	23	29	65.5	79.3	100
2004	31	18	20	100	58.1	64.5
2005	28	19	10	100	67.9	35.7
2006	20	18	11	100	90	55
Total score				923.2	695.2	692.7
Average score				92.3	69.5	69.3

3.4. *Band allocation*

We have adopted a more generalized research performance ranking system, so as to support and encourage the universities in their efforts to establish continuous excellence in IC design research. In the usual individual ranking approach, the rank positions are determined by the absolute scores to one (or even more) decimal point, which in effect does not translate to a meaningful difference in performance. Henceforth, besides individual ranking of each university based on absolute scores, we have also grouped in bands the universities with similar research performance. This approach provides another dimension for ranking analysis. Table 2 shows the five band allocations depending on the average scores of the universities.

A flowchart illustrating the entire methodology used for ranking is shown in Fig. 2.

4. Results and Analysis

In this section, we present statistically our results on the band distributions of universities based on varying ranking indicators: *Number of Publications*, *Citation Counts*, and *Cites per Paper*. It is worth mentioning here that a university that falls into a particular band with *Number of Publications* being the ranking indicator need not necessarily fall into the same band when *Citation Counts* or *Cites per Paper*

Table 2. Band allocation.

Band	Score X (%)
I	$X \geq 70$
II	$50 \leq X < 70$
III	$30 \leq X < 50$
IV	$20 \leq X < 30$
V	$0 \leq X < 20$

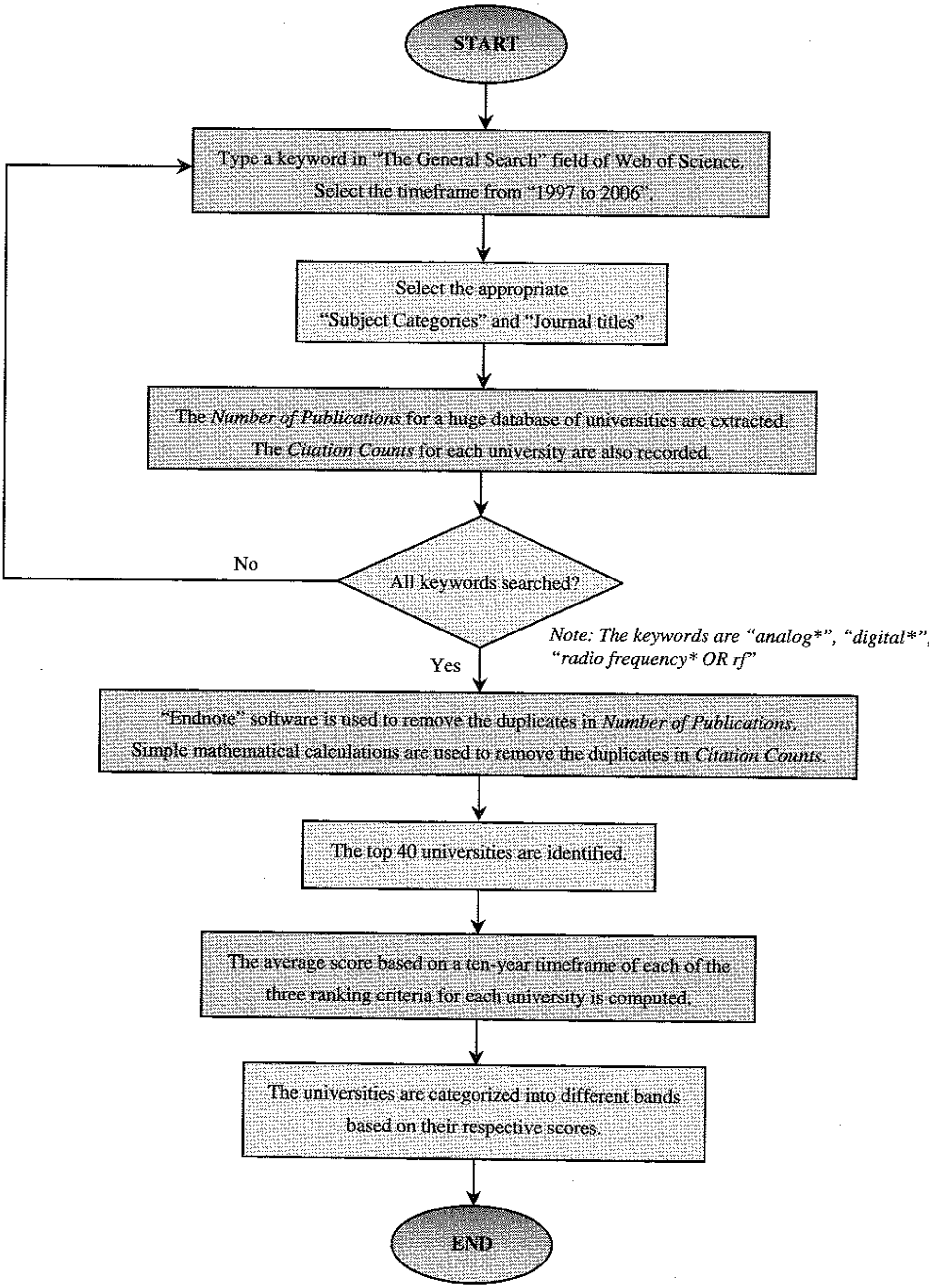


Fig. 2. Flowchart for IC design ranking of worldwide universities.

are considered. On top of that, the Who's Who in each IC design fields, namely Analog IC, Digital IC, and RF IC are also identified alongside graphical illustrations of their yearly research contributions. Each university appearing in the graphs is assigned with a unique legend for ease of reference.

4.1. *Classification of universities based on Number of Publications*

The top 40 universities are categorized into different bands according to their respective average scores when the *Number of Publications* is used as the ranking criteria. Table 3 compiles the number of universities in each band. The universities clustered within a particular band are progressing on par with one another over the time span of ten years.

Figure 3 displays graphically the band distribution of the universities based on the *Number of Publications.* The shaded regions with varying widths represent the actual range of scores occupied by the universities in the respective bands. For instance, Table 3 shows that Band II represents the scores of 50–70%. However,

Table 3. Band allocation based on *Number of Publications.*

Band	Score X (%)	Number of universities
I	$X \geq 70$	2
II	$50 \leq X < 70$	7
III	$30 \leq X < 50$	25
IV	$20 \leq X < 30$	5
V	$0 \leq X < 20$	1

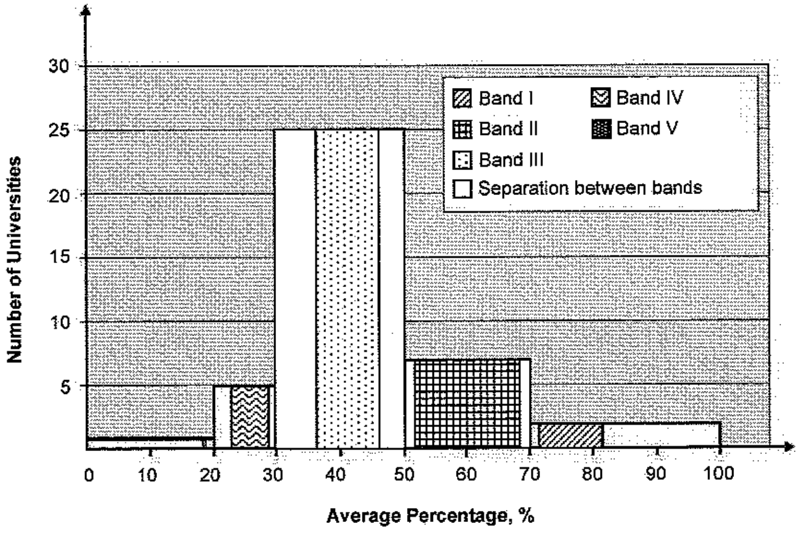


Fig. 3. Band distribution for *Number of Publications.*

the actual scores of the seven universities which fall within Band II, as indicated by the grid legend in Fig. 3, are within the range of 51.9–68.5% instead of 50–70%. Hence, the grid legend does not occupy the entire bar of 50–70% but only occupies the range of 51.9–68.5% within that bar. In other words, the widths of the shaded bands vary depending on the actual scores of the universities that fall within that particular band. Moreover, it can be observed that most of the universities are allocated in Band III. One possible reason is that all these institutions have similar rate of progress in terms of *Number of Publications* per year and hence achieve scores that fall into the category of Band III. Based on the *Number of Publications*, only two universities, namely University of California, Los Angeles and Nanyang Technological University occupy Band I.

It is beneficial and informative for the readers to be aware of the universities that fill the top positions in the respective fields of IC design. This would serve as a great tool to assist the readers to make informed decisions with respect to the individual field. In view of that, we have also compiled each university's publication statistics based on specific IC design fields to analyze the progress of each university in paper publication on a yearly basis. The bar charts showing the annual trend of *Number of Publications* for five most prominent universities in Analog IC, Digital IC, and RF IC design fields are presented in Figs. 4, 5, and 6, respectively.

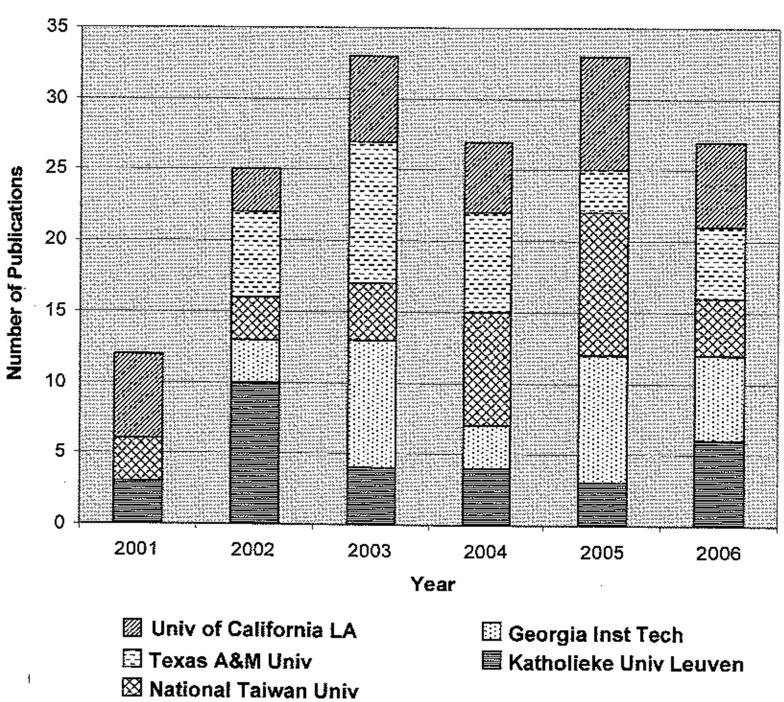


Fig. 4. Analog IC top five performers in *Number of Publications* for the past six years.

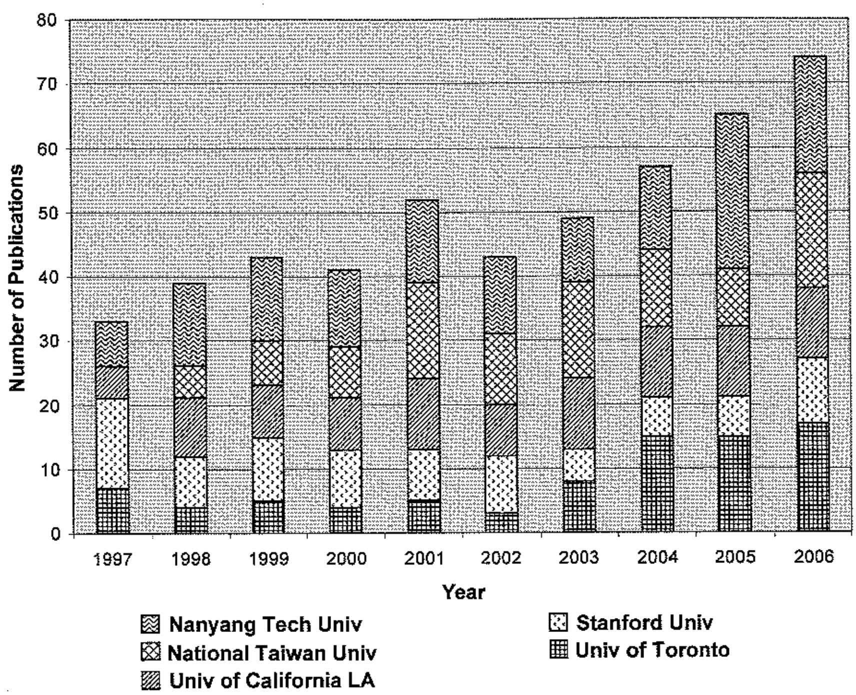


Fig. 5. Digital IC top five performers in *Number of Publications* for the past ten years.

While banding is an applausive approach to effectively gauge the competitiveness of the universities, it is also important to note that the Band I universities, specifically University of California, Los Angeles, and Nanyang Technological University, may not necessarily be among the top five performers in all three IC design fields. This would mean that when the *Number of Publications* are divided separately into Digital IC, Analog IC, and RF IC and plotted into graphs, the two universities may not appear in all of the graphs. However, it is reasonable that each of the two universities will appear at least once in the separate graphs of Digital IC, Analog IC, and RF IC publications. This is a noteworthy point because while a particular university of Band I in the *Number of Publications* performs well in the field of Digital IC, it may lose out to its other counterparts in the fields of Analog IC and RF IC. One good example that fits into this analogy is the Nanyang Technological University, which is the topmost performer in Digital IC design, as shown in Fig. 5. However, its research publications is not superior in the fields of Analog IC and RF IC, hence its name is absent in Figs. 4 and 6.

Figure 7 shows the percentage distribution of the *Number of Publications* for the top 40 universities over a span of ten years with respect to the specific fields of Digital IC, Analog IC, and RF IC design. Digital IC accounts for exactly half of the total share followed by RF IC and Analog IC, each contributing 34% and 16%.

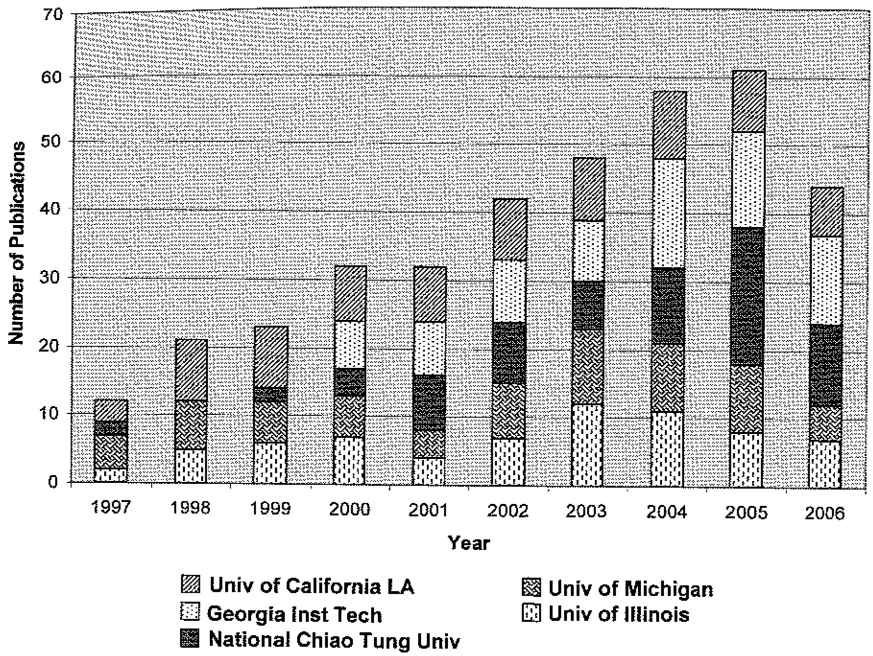


Fig. 6. RF IC top five performers in *Number of Publications* for the past ten years.

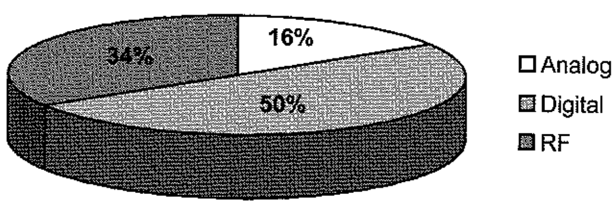


Fig. 7. Distribution of *Number of Publications* based on different IC design fields.

4.2. *Classification of universities based on Citation Counts*

Table 4 tabulates the band allocations of the 40 universities based on *Citation Counts*, while Fig. 8 shows the distribution in a pictorial manner. Two universities, namely Stanford University and University of California, Los Angeles grace the top spots (Band I) in this category.

It can be observed that most of the universities fall into Band V. This suggests that there is a big discrepancy in the frequencies of the publications being cited between the top performer and a majority of its other counterparts.

With the *Citation Counts* taken as the ranking indicator, top five performers in the Analog IC, Digital IC, and RF IC design fields are identified and the yearly trends are shown in Figs. 9, 10, and 11, correspondingly. From the illustrations,

Table 4. Band allocation based on *Citation Counts*.

Band	Score X (%)	Number of universities
I	$X \geq 70$	2
II	$50 \leq X < 70$	3
III	$30 \leq X < 50$	6
IV	$20 \leq X < 30$	8
V	$0 \leq X < 20$	21

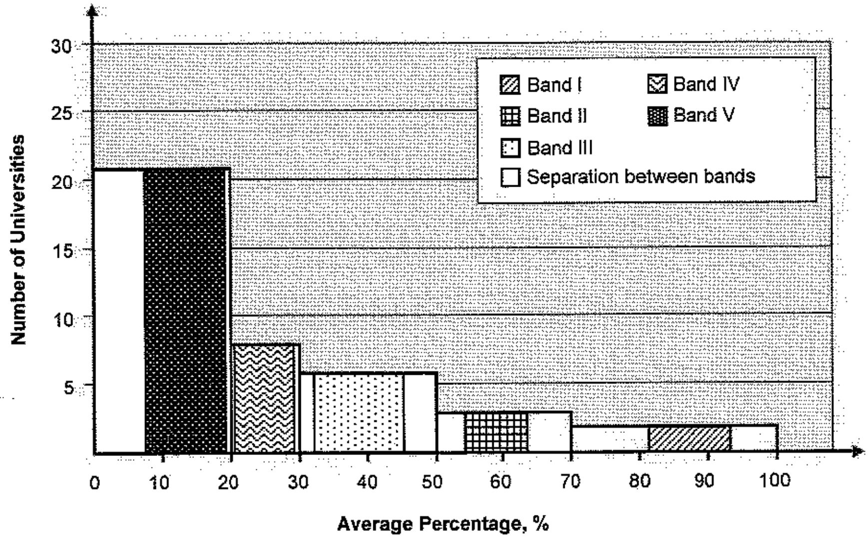


Fig. 8. Band distribution for *Citation Counts*.

we observe that even though Stanford University and University of California, Los Angeles exhibit impressive *Citation Counts* in all fields, the *Citation Counts* of almost all other competitors have also been gradually and steadily increasing over the years. Due to a substantially lower *Citation Counts* in the earlier years, we have included an inset bar chart in Figs. 9–11 to better exemplify the *Citation Counts* of the universities within the time span.

Figure 12 shows the *Citation Counts* percentage breakdown in each IC design fields of Analog IC, Digital IC, and RF IC for the top 40 universities over the ten-year timeframe. Digital IC design occupies more than half of the total share, followed by RF IC (36%) and Analog IC (9%).

4.3. *Classification of universities based on Cites per Paper*

The band allocations of the top 40 universities based on the ranking criteria of *Cites per Paper* is shown in Table 5, while its graphical representation is portrayed in Fig. 13. None of the universities managed to meet the score requirement of Band I.

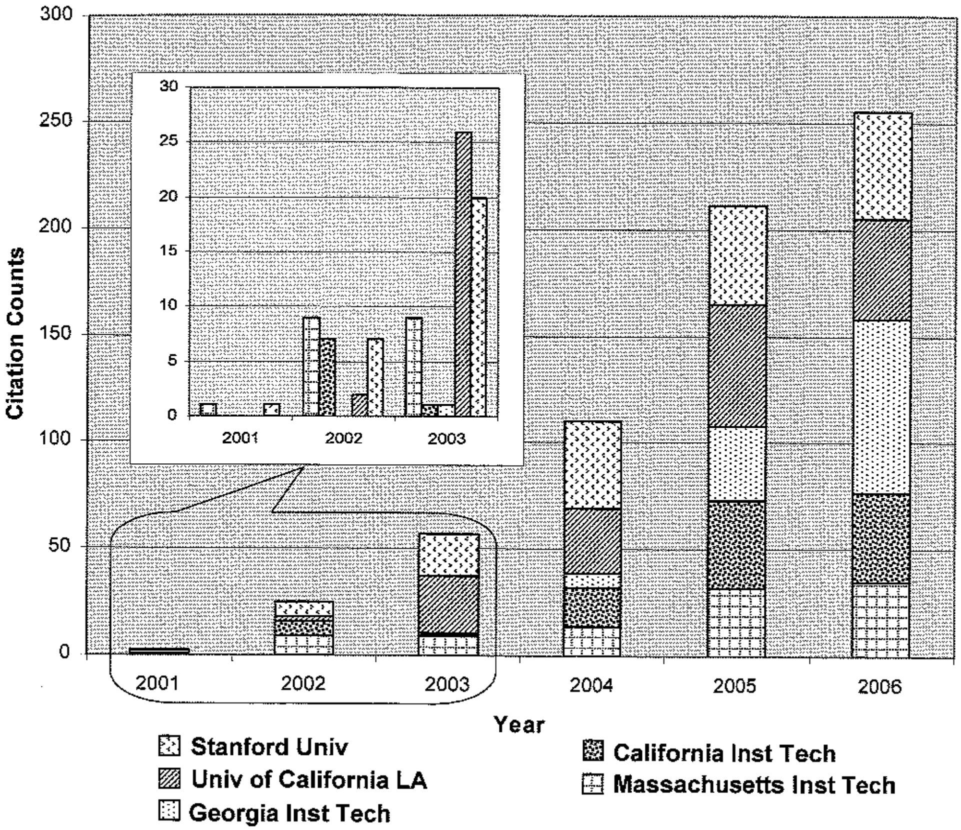


Fig. 9. Analog IC top five performers in *Citation Counts* for the past six years.

This implies that the research performance of all the universities in conjunction with *Cites per Paper* has been inconsistent throughout the ten-year period. Meanwhile, two universities, namely University of California, Berkeley and Stanford University are grouped in Band II.

Most of the universities are clustered in Bands III, IV, and V, with similar number of universities in each band. In Figs. 14–16, the trends for *Cites per Paper* on a yearly basis for each IC design fields are shown with their respective top five universities. Similar to Sec. 4.2, an inset bar chart has been included in Figs. 14–16 to clearly illustrate the *Cites per Paper* of the universities within the given time span. Stanford University peaks the *Cites per Paper* in the fields of Analog IC and RF IC design but comes fourth in Digital IC.

Figure 17 shows the *Cites per Paper* percentage distribution in terms of the individual fields of Digital IC, Analog IC, and RF IC design for the top 40 universities over the past 10 years. Digital IC accounts for a 41% share of the total *Cites per Paper*. The share of RF IC is comparable to that of Digital IC, which is at 39%, while Analog IC accounts for 20% of the total share.

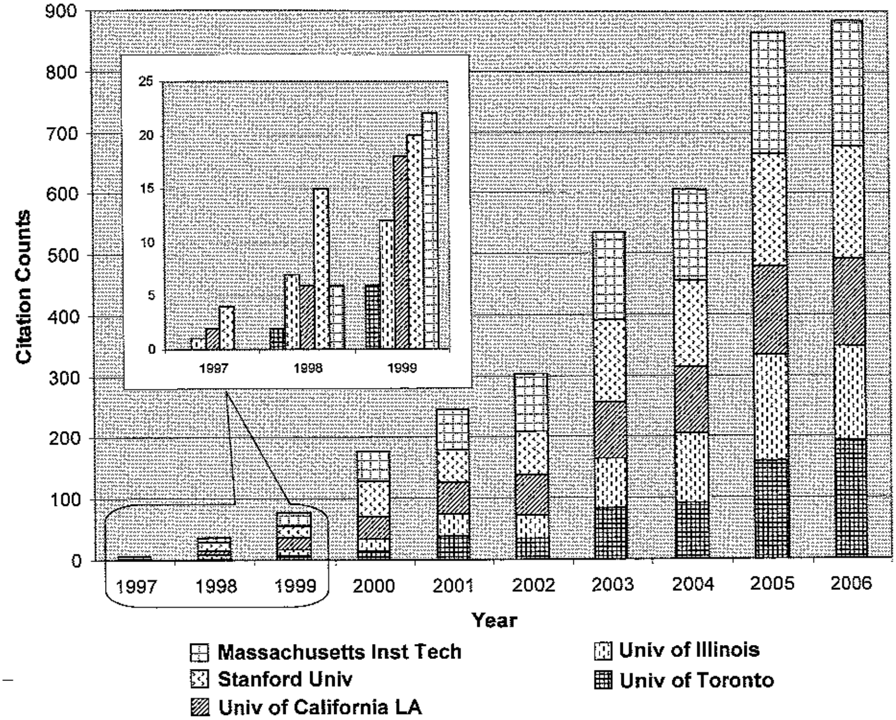


Fig. 10. Digital IC top five performers in *Citation Counts* for the past ten years.

4.4. *Findings and discussions*

A comprehensive list detailing the overall band allocation of the top 40 universities in IC design research based on the average scores of the three ranking indicators is tabulated in Table 6. The ranking indicators are given equal weight as all three are of significant importance. While banding provides us with a new dimension for ranking assessment, the absolute scores obtained by each university are also included in the table to facilitate individual ranking. US universities fill the top spots in the ranking. Stanford is at the helm of the overall ranking and it is the only university that qualifies to be grouped in Band I, mainly attributed to its exceptionally good performance in the *Citation Counts* criterion. Meanwhile, four universities, namely University of California, Los Angeles, University of California, Berkeley, Massachusetts Institute of Technology, and University of Illinois, occupy Band II. A vast majority of the universities fall into Bands III and IV, while only two contenders are categorized in Band V. The highest ranking non-US university is the University of Toronto from Canada, whereas the highest ranking university in the Asian continent is the National Taiwan University, both clustered in Band III. We have also provided the number of personnel, which is a breakdown of the faculty, postgraduate students, and researches involved in IC design for each university as

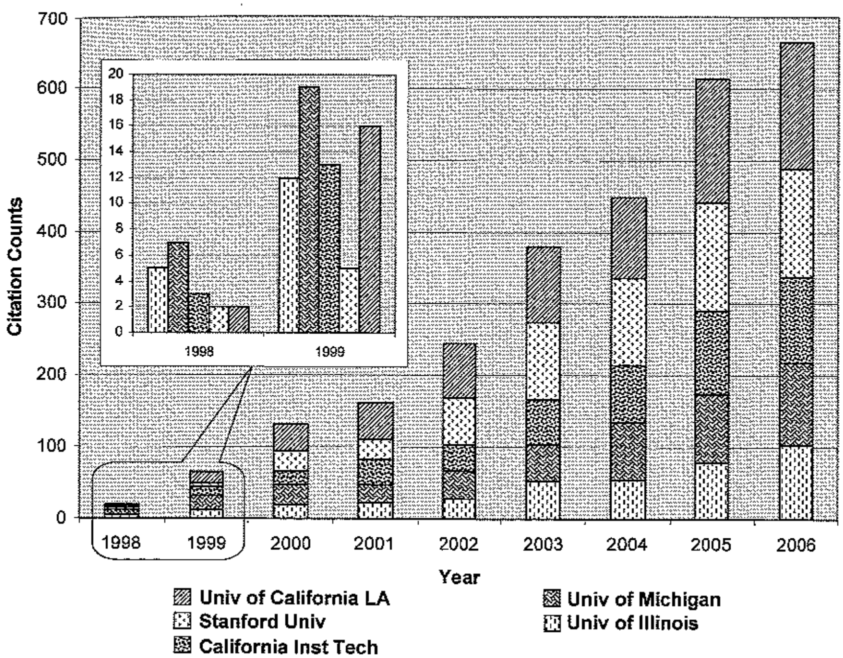


Fig. 11. RF IC top five performers in *Citation Counts* for the past six years.

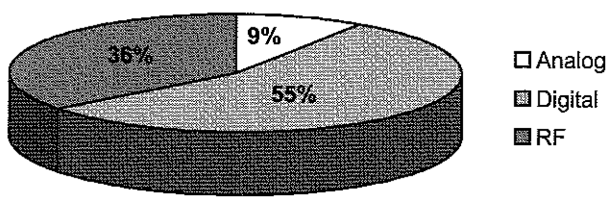


Fig. 12. Distribution of *Citation Counts* based on different IC design fields.

Table 5. Band allocation based on *Cites per Paper*.

Band	Score X (%)	Number of universities
I	$X \geq 70$	0
II	$50 \leq X < 70$	2
III	$30 \leq X < 50$	10
IV	$20 \leq X < 30$	13
V	$0 \leq X < 20$	15

of October 2007 alongside their band allocations. One may note that a number of world-renowned big-name universities such as Harvard University (US), Cambridge University (UK), and Oxford University (UK) are not seen in the list. This is because these universities emphasize more on the other areas of the academic realm, e.g., biomedicine, science, arts and humanities, etc.[8]

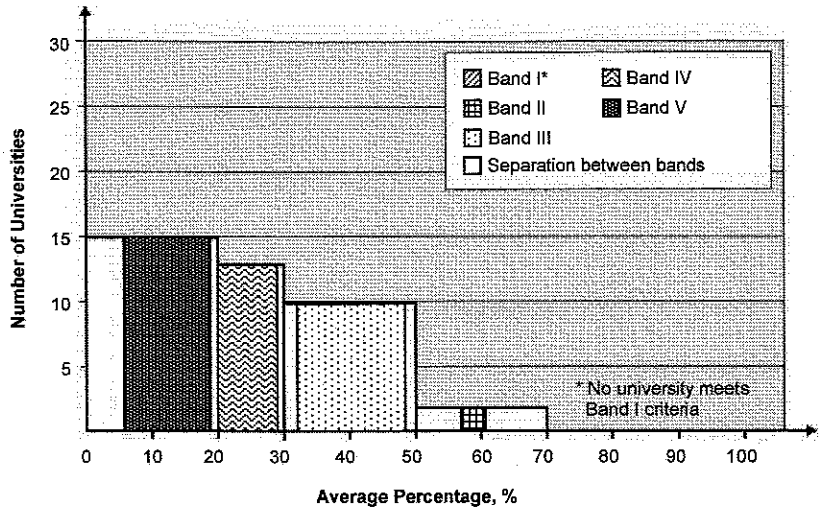


Fig. 13. Band distribution for *Cites per Paper*.

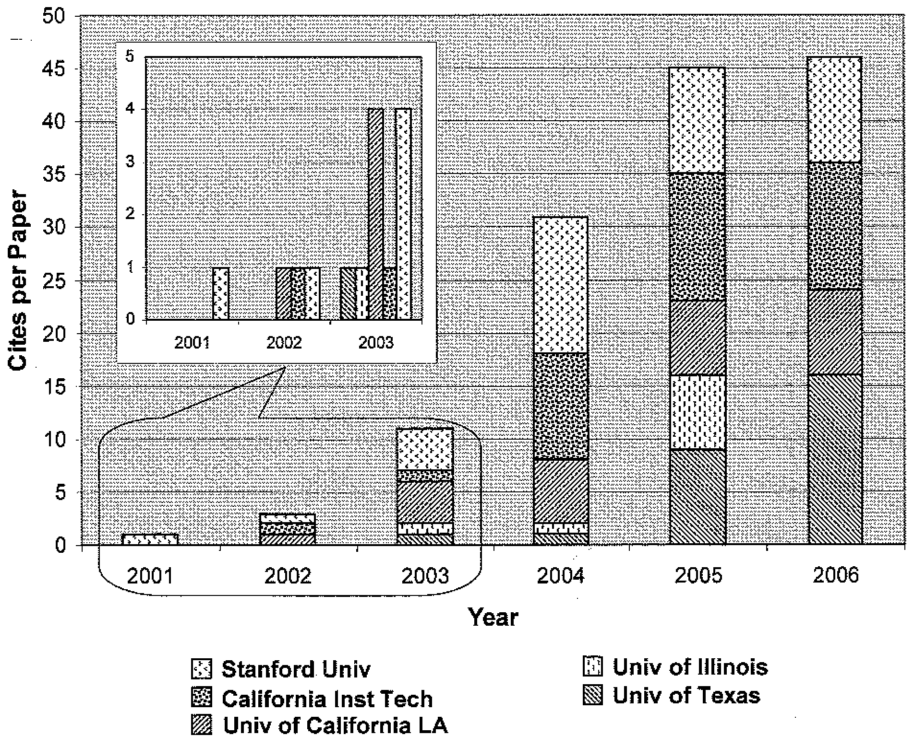


Fig. 14. Analog IC top five performers in *Cites per Paper* for the past six years.

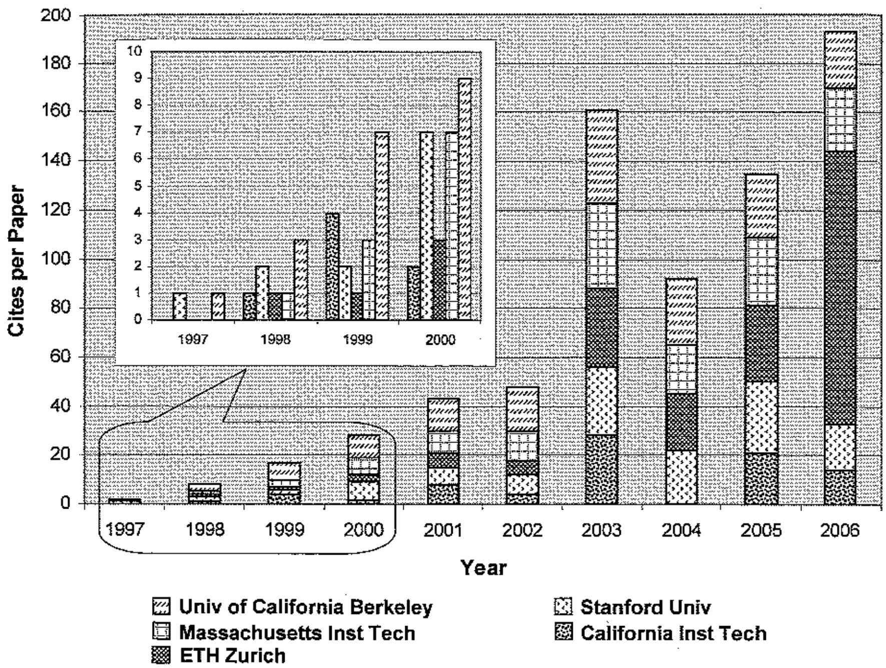


Fig. 15. Digital IC top five performers in *Cites per Paper* for the past ten years.

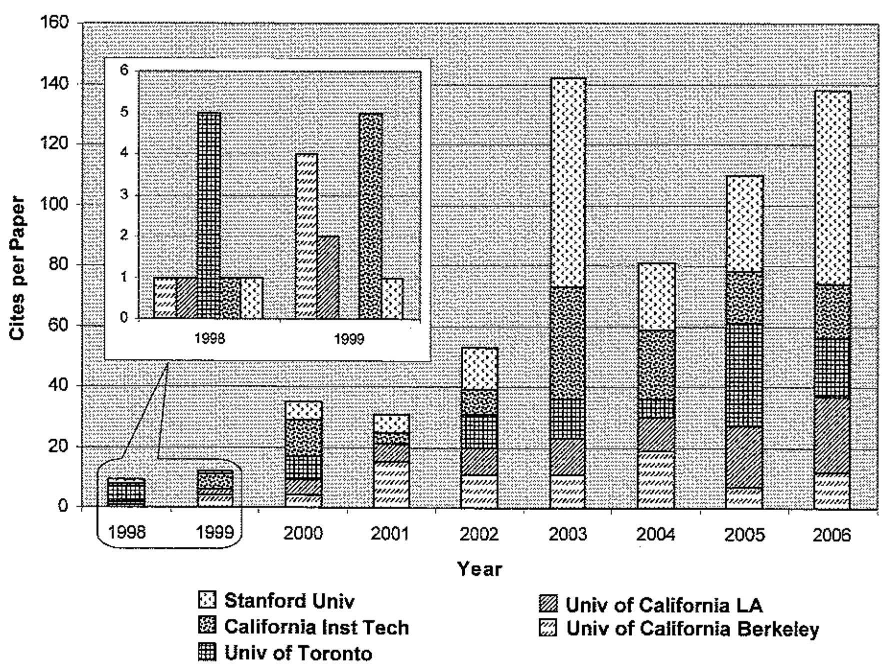


Fig. 16. RF IC top five performers in *Cites per Paper* for the past nine years.

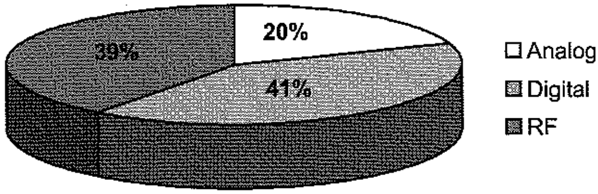


Fig. 17. Distribution of *Cites per Paper* based on different IC design fields.

In addition, from the detailed statistics presented earlier, we observe that a number of universities have performed particularly well, some have done fairly well, while the others were lagging behind. The underlying root cause of the performance gap are important for university administrators, academics, researchers, students or even the government officials to ponder upon so that they can emulate the successful model in their effort to enhance their position in the global arena. In this section, we examine the role model set by leading universities (in particular their research centers) and identify a three-pronged approach to yielding outstanding research performance.

IC design requires constant brainstorming and innovations that can be described as of an intellectually arduous nature. Thus, to stay competitive on a global scale, *human capital and talent* is a critical component of the equation. A team of dedicated researchers who are technically precocious and committed to take ownership of their research work is essential to elicit good research publications. These researchers are usually led by faculty members, who are the vanguard committed to provide the researchers and students with judicious and insightful technical expertise in IC design. They are also capable to appropriately shape and reshape their research strategy and direction in a timely manner in response to the ever-changing scale and scope of the education and electronic/semiconductor industry landscape. Quality not quantity is of foremost importance here. For instance, the IC design research group in California Institute of Technology is probably one of the most prominent IC think-tank in the world even though it is formed by a relatively small number of seven faculty members. Research activities at Caltech include, among others, "Circuits and VLSI" and "RF, Microwave Circuits, and Antenna".

The second approach is by establishing a *close academia–industry collaboration*[13] to promote sharing of knowledge and potential commercialization of design ideas. The universities will become more effective working with major players in IC related industries on large-scale and long-term research projects. This is important not only for bringing in funding, but will also help generating new IC innovations and ideas to fuel the development of new products and processes as well as building a competent and cohesive research team. In addition, a strong and vibrant relationship with the collaborators will keep the universities positioned at the cutting edge of design and key technologies. In fact, during the course of our extensive search of IC design related research publications, we observed an encouraging phenomenon,

Table 6. The top 40 universities in IC design research.

Rank	Overall Band	Overall Score	University	Country	Number of Publications Band	Number of Publications Score	Citation Counts Band	Citation Counts Score	Cites per Paper Band	Cites per Paper Score	Number of personnel involved in IC design as of October 2007: Faculty	Postgraduates	Researchers
1	I	72.0	Stanford Univ	US	II	65.5	I	93.1	II	57.3	15	100	20
2	II	66.3	Univ of California, Los Angeles	US	I	82.4	I	81.2	III	35.2	14	80	20
3	II	54.4	Univ of California, Berkeley	US	III	38.5	II	64.6	II	60.3	23	130	30
4	II	53.7	Massachusetts Inst of Technology	US	II	51.9	II	63.2	III	46.1	19	100	25
5	II	50.9	Univ of Illinois	US	II	59.2	II	54.6	III	38.8	14	50	10
6	III	43.7	Univ of Michigan	US	II	53.5	III	43.8	III	33.7	20	94	10
7	III	43.5	California Inst of Technology	US	III	36.6	III	45.0	III	48.8	7	50	28
8	III	43.5	Univ of Toronto	Canada	III	45.1	III	42.7	III	42.6	21	90	5
9	III	43.3	Katholieke Univ Leuven (Flemish)	Belgium	III	40.4	III	41.7	III	47.8	18	55	30
10	III	41.7	National Taiwan Univ	Taiwan	II	68.5	III	36.2	IV	20.5	23	190	5
11	III	35.2	Georgia Inst of Technology	US	II	54.1	III	32.4	V	19.2	12	90	14
12	III	33.3	Delft Univ of Technology	Netherlands	III	34.9	IV	29.8	III	35.2	20	75	18
13	III	32.6	ETH Zurich	Switzerland	III	34.4	IV	28.0	III	35.5	6	50	12
14	III	31.9	National Chiao Tung Univ	Taiwan	II	64.9	V	19.8	V	11.1	20	56	1
15	III	31.4	Helsinki Univ of Technology	Finland	III	47.0	IV	26.5	IV	20.7	5	9	35
16	III	30.7	Nanyang Technological Univ	Singapore	I	72.5	V	13.6	V	5.9	21	200	24
17	III	30.4	Hong Kong Univ of Sci & Tech	Hong Kong	III	36.6	IV	25.3	IV	29.4	11	50	15
18	IV	29.6	Univ of Maryland	US	III	32.5	IV	24.3	III	31.9	10	25	4
19	IV	28.2	Univ of California, San Diego	US	III	37.9	IV	23.0	IV	23.7	11	35	5
20	IV	27.8	Univ of Minnesota	US	III	37.5	IV	22.5	IV	23.4	8	32	3
21	IV	26.4	Univ of Tokyo	Japan	III	39.6	IV	22.2	V	19.5	10	21	2
22	IV	25.6	Texas A & M Univ	US	III	45.7	V	15.8	V	15.2	6	34	3
23	IV	25.3	Univ of Texas	US	III	39.9	V	18.7	V	17.3	15	95	6
24	IV	24.7	Korea Advanced Inst of Sci & Tech	Korea	III	47.6	V	15.2	V	11.5	10	48	1
25	IV	24.6	National Cheng Kung Univ	Taiwan	III	44.2	V	16.3	V	13.4	14	73	1

Table 6. (*Continued*)

Rank	Overall Band	Overall Score	University	Country	Number of Publications Band	Number of Publications Score	Citation Counts Band	Citation Counts Score	Cites per Paper Band	Cites per Paper Score	Number of personnel involved in IC design as of October 2007: Faculty	Postgraduates	Researchers
26	IV	23.5	Purdue Univ	US	III	30.7	V	18.8	IV	21.1	12	50	15
27	IV	23.2	Osaka Univ	Japan	III	31.2	V	17.3	IV	21.2	7	23	7
28	IV	23.1	Polytechnic Univ of Turin	Italy	III	35.9	V	17.0	V	16.3	5	10	12
29	IV	23.0	Univ of Waterloo	Canada	IV	29.0	V	16.0	IV	24.2	16	76	4
30	IV	22.1	National Univ of Singapore	Singapore	III	42.5	V	12.4	V	11.5	9	15	5
31	IV	22.1	Univ of Pavia	Italy	III	31.4	V	12.8	IV	22.0	11	24	5
32	IV	21.9	Univ of California, Davis	US	IV	24.8	V	15.9	IV	24.9	6	19	2
33	IV	21.8	Oregon State Univ	US	IV	26.9	V	13.6	IV	24.8	10	31	2
34	IV	21.7	Univ of Bologna	Italy	III	30.4	V	12.6	IV	22.3	10	35	21
35	IV	21.0	Tohoku Univ	Japan	III	37.4	V	11.9	V	13.7	15	27	3
36	IV	20.3	Univ of Victoria	Canada	V	19.7	V	12.2	IV	29.0	8	11	1
37	IV	20.2	Seoul National Univ	South Korea	III	40.1	V	10.2	V	10.3	18	33	21
38	IV	20.1	Polytechnic Univ of Milan	Italy	IV	29.3	V	12.2	V	18.7	10	21	14
39	V	18.1	Tokyo Inst of Technology	Japan	III	36.7	V	9.8	V	7.9	7	28	2
40	V	16.2	Tampere Univ of Technology	Finland	IV	27.9	V	7.8	V	12.9	4	15	26

Univ: University. Inst: Institute.

i.e., there have been a substantially increasing number of articles, which are the results of joint collaboration between universities and industrial companies.

A good example of close cooperation with the industry is the Berkeley Wireless Research Center (BWRC) at the University of California, Berkeley. It emerged in 1998 with seven founding members from the industry including Cadence, Ericsson, and Hewlett Packard. Its member companies expanded to 23 in 2007 with new entrants such as Motorola and Nokia Research.[14,15] In fact, through its distinguished industry–academia collaborative research model, it has become one of the centers responsible for spearheading the international realm of IC design research. Since its inauguration, it has successfully bagged six best paper awards at the high-prestige International Solid State Circuit Conference. In Europe, the Microelectronics and Sensors group (MICAS) of Katholieke University Leuven, has only six professors and 75% of their research activities are carried out through partnerships with the industries. They are marching towards their mission of providing education and research in the field of analog, digital, and mixed-signal integrated circuit and sensor design at the highest possible scientific level and are gaining worldwide recognition. The MICAS has thus far set up four spin-off companies, namely ICsense, Ansem, Kimotion Technologies, and Mephisto Design Automation. Katholieke University Leuven resides in Band III of our ranking and it is the top European university when absolute score is considered. In addition, the National Taiwan University, which is the top Asian university grouped in Band III, has also established dedicated partnerships with the industry. It has formed an organization named the System-on-Chip (SoC) Centre to promote exchange of research results between academia and industry.[16] In Singapore, the Nanyang Technological University has currently 21 faculty members involved actively in IC design related research activities. It is allocated within Band III and ranked a decent 16th as far as individual ranking is concerned. The Division of Circuits and Systems, the Centre for Integrated Circuits and Systems (CICS) and the Centre for High Performance Embedded Systems (CHiPES) are among the leading forces in IC design research. They have forged strong collaborations with the industry focusing mainly on mixed signal, RF, Very-Large-Scale Integration (VLSI), SoC, and System-in-Pacakge (SiP) designs.

Although a few non-US universities have found their places among the top rungs in our ranking, it is apparent that US universities have been consistently maintaining the topmost positions. A major contributor to this consistency is largely due to the *sizeable amount of endowment* from both the government and industrial companies. IC design research is not just about paper work or mere computer simulations. Actual physical circuit implementation, circuit integration, analysis, measurement, and testing are required from time to time to verify the proof-of-concept with particular emphasis on practical applications. These are the requisite requirements for an article to qualify for publication in prestigious journals. In view of that, substantial amount of funding can definitely boost the research activities in any institution, such as to bring in highly sophisticated research equipment and infrastructure.

The United State had invested a vast amount of about 250 billion USD on higher education yearly.[9] Thus, it is understandable that top institutions like Stanford University and University of California, Los Angeles are always well resourced, which correlates to their good research output and high ranking among global universities. The universities are always equipped with technically well-supported research centers and laboratories in the area of IC design. All these laboratories are endowed with state-of-the-art facilities, which are vital to the IC design development of the university.

5. IC Design Statistical Analysis Based on Geographical Region

We now analyze the annual trend of research output in each IC design field from another perspective, i.e., the different regions of the world, namely the United States, Europe, Japan, and Asia (excluding Japan). The *Number of Publications* for the worldwide regions for the Analog IC, Digital IC, and RF IC design fields are portrayed in Figs. 18, 19, and 20, respectively.

From the three graphs, it is apparent that the United States is the mainstay winner as it publishes the most number of papers in all three IC design fields for the given timeframe. The Europe region has maintained its first runner-up position particularly in Analog IC but as for Digital IC and RF IC, it was taken over by its Asia counterpart in the later years: 2004 (digital) and 2002 (RF). Japan and Asia have almost similar number of papers in Analog IC design. While their shares became comparable to each other in 1997–1999 in both fields of Digital IC and RF IC, Asia's *Number of Publications* took off tremendously from 2000 onwards to the extent that it surpassed not only that of Japan but also the Europe region. Therefore, it is reasonable for us to comment that the Asia region is increasingly

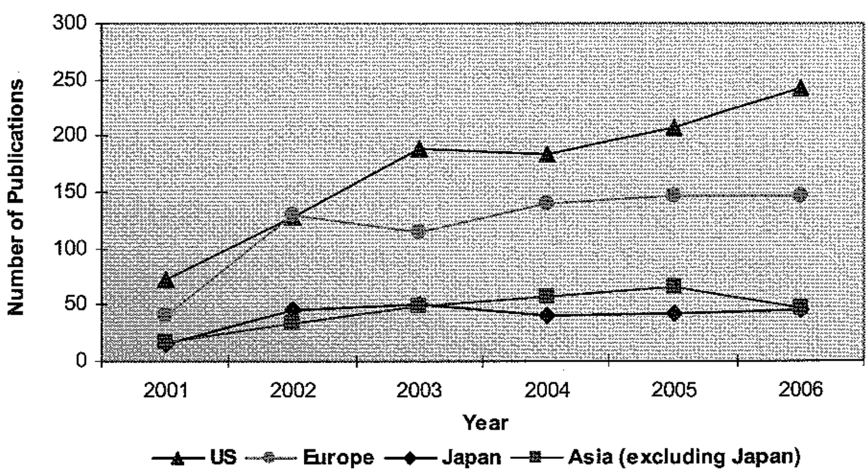


Fig. 18. Analog IC design *Number of Publications* for different regions of the world.

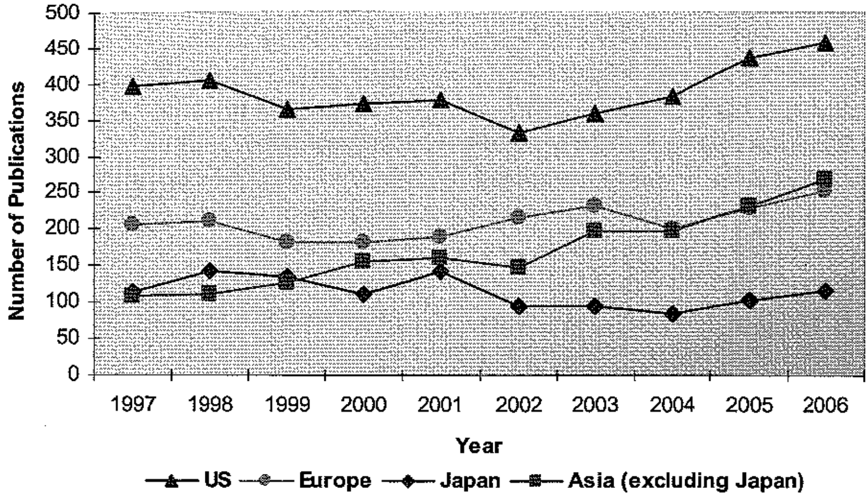


Fig. 19. Digital IC design *Number of Publications* for different regions of the world.

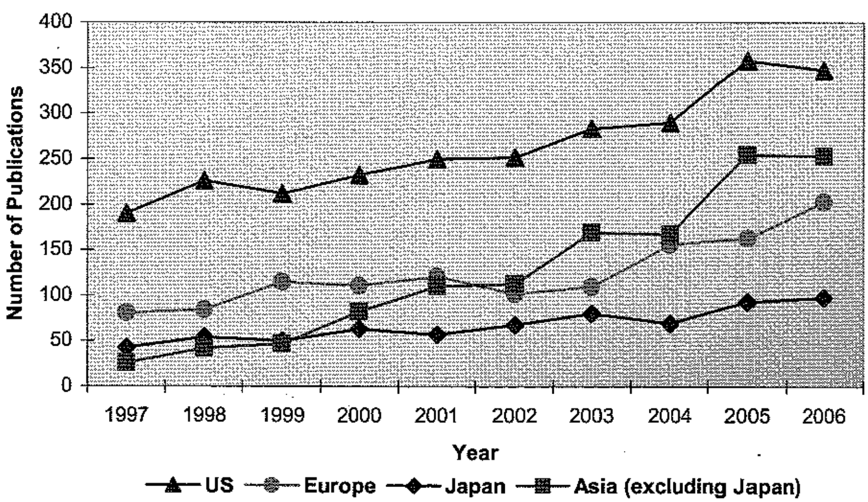


Fig. 20. RF IC design *Number of Publications* for different regions of the world.

gaining its prominence in the IC design field and it is a growing force not to be reckoned with.

The top 10 countries in IC design research for the specific fields of Analog IC, Digital IC, and RF IC are tabulated in Tables 7, 8, and 9, correspondingly. Singapore is also included in the comparison because it has made remarkable progress and invested significantly in IC design. As a result, it has attracted a lot of IC design related activities and produced the highest publication numbers per person recently. The United States is the all-time top performer producing a consistent,

Table 7. *Number of Publications* in analog IC design for different countries.

Country	Year					
	2001	2002	2003	2004	2005	2006
US	62	114	168	162	181	196
Japan	15	45	50	40	42	45
Italy	13	44	40	29	34	42
Spain	7	33	22	40	36	27
Canada	11	14	20	21	27	47
Germany	7	25	16	22	34	21
Taiwan	6	15	21	26	34	23
France	7	12	24	23	19	34
South Korea	11	14	24	27	22	19
England	7	15	12	26	24	23
Singapore	0	4	4	4	9	5

Table 8. *Number of Publications* in digital IC design for different countries.

Country	Year									
	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006
US	339	346	324	334	342	289	305	320	357	368
Japan	114	142	134	112	144	94	96	84	104	117
Italy	70	72	58	62	84	80	96	75	78	95
South Korea	46	40	59	48	57	52	68	66	79	86
Canada	58	60	41	38	36	44	54	63	80	90
Taiwan	49	30	34	61	52	45	66	61	70	75
Germany	47	57	55	39	48	58	53	41	65	55
England	55	51	43	55	30	47	39	45	47	53
China	4	20	14	29	31	34	44	51	50	80
France	34	31	27	26	29	31	44	40	41	50
Singapore	9	22	21	17	21	18	20	20	33	30

Table 9. *Number of Publications* in RF IC design for different countries.

Country	Year									
	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006
US	171	207	184	215	237	229	251	263	309	293
Japan	43	54	50	63	57	68	80	69	93	98
South Korea	12	17	23	25	41	37	51	57	83	77
Taiwan	11	17	13	23	37	29	45	56	85	85
Germany	36	27	39	28	47	28	36	58	52	49
France	9	26	27	33	28	22	25	36	44	65
Canada	19	19	28	17	13	23	32	27	49	55
Italy	12	13	21	19	24	24	28	34	41	58
China	3	5	6	17	24	27	36	35	52	68
England	24	18	28	31	22	28	20	28	26	31
Singapore	0	3	5	17	8	20	37	19	35	23

if not increasing number of publications as the year progresses in all IC design fields. It is leading its other contenders by a big margin and has published thrice as many papers when compared to Japan, which is in the second position, in all the three IC design fields. Another noteworthy observation is that, China, having emerged from its fabless start-up phase, has seen a steadily increasing trend in paper publications in the fields of Digital IC and RF IC. Singapore has published considerably less number of papers as compared to the top ten, but an encouraging fact is that it has shown noteworthy improvements over the years especially in the Digital IC and RF IC design fields.

6. Conclusions

The ranking of worldwide universities to assess their research performance, especially in a specific field, entails many benefits. First, it allows each university to be aware of its standing in the global arena. Armed with this knowledge, the university's management can then set a visible and yet reasonable goal for the university to strive forward diligently as well as devising strategic plans to outperform its competitors in the near future. Second, prospective students who are interested in a specific field may make use of the ranking results as a general guideline to select the institution that they would like to enroll in. Third, employers may refer to the ranking as an additional yardstick to peg the compensation package for their prospective employees.

However, while rankings in a specific area of specialty, such as software engineering, and computer science are already available in the open literature, the same does not apply for the specialized field of IC Design. It is the core pillar of one of the largest industries in the world, namely the semiconductor industry. In fact, according to recent statistics from the Global Semiconductor Alliance, GSA (previously known as Fabless Semiconductor Association, FSA), fabless IC sales suppliers have seen a fabulous 25% Compound Annual Growth Rate (CAGR) from 1998 to 2006, which is amongst the highest in the semiconductor industry.[17] Hence, there is a need to perform ongoing assessment and benchmarking of the progress of universities in IC design research, in a global scene.

With this in mind, we have conducted the first-ever worldwide universities research performance ranking in the specialized field of IC design, based on three ranking indicators, namely, *Number of Publications*, *Citation Counts*, and *Cites per Paper*. In our methodology, we have adopted a more generalized research performance ranking system, so as to support and encourage the universities in their endeavor to strive for continuous excellence in IC design research. Besides individual ranking of each university based on absolute scores, we propose to group in bands the universities with similar research performance. This approach provides another perspective for ranking analysis.

Ultimately, the most prominent 40 universities gracing the top echelons in IC design research are identified. Interesting statistics and findings based on the specific fields of IC design: Analog IC, Digital IC, and RF IC are also reported in the paper.

While there may still be room for improvement in our ranking approach, we will continuously strive toward perfecting it and we are hopeful that our ranking will provide the IC design community with first-hand knowledge of how they fare against their peers. On top of afore-said, based on our meticulous observations on the top performers, we introduced a three-pronged prerequisite for yielding excellent research performance. The comparisons of research outputs based on different geographical regions are also reported to provide readers with a clearer picture of the IC design research and trends.

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