Reintroducing Six Sigma DMAIC Processes using a Hands on Approach

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Abstract— **In recent years industries and colleges have had a greater need for improved six sigma training. Presented in the following paper will be an up to date analysis of the current six sigma curriculum being taught here at Bradley University. This paper attempts to address the problem with the lack of educational training engineers have when entering a six sigma improvement process for their given industry. With the help of peer evaluations, in class lectures and, hands on projects, will an improved curriculum be introduced. In order to present this course, a case study following a 3D printing team using the DMAIC six sigma methodologies will be further analyzed.**

I. Introduction

As a private university, Bradley University's Caterpillar College of Engineering and Technology (CCET) plays an important role in helping provide well-rounded engineers to industries in this region including Peoria, Chicago, St Louis, Indianapolis. The main industries housed in this region, named and not limited to, are Caterpillar, John Deere, and Boeing. There are more than 5,000 companies also serving this region, some of which are key suppliers for the abovementioned main companies. Bradley University specifically has a strong tie with Caterpillar, where a few top level VPs are CCET alumnus.

These major companies have been faced with increasing amounts of pressure from customers and competitors in the past couple of decades. Customers have higher expectations from their purchases, and manufacturers can meet these expectations by increasing a product's quality, reducing delivery time, and minimizing product costs—or a combination of the three (George 2002). This has forced the manufacturing industry to implement new production strategies to enhance their competitiveness in the global market. One of these strategies is "Six sigma." Which is used to improve already existing processes and had been proven to be successful in reducing costs, improving cycle times, eliminating defects, raising customer satisfaction and significantly increasing profitability in many organizations worldwide (Tong et al., 2004)

In one recent article, several research groups indicated that there is more demand for skill and education from colleges or universities whom of which have failed to provide its student engineers with the knowledge to succeed right after entering the work force[1]. Thus it relies on the corporation to implement educational institutions to conduct further training to their new engineers. One of such additional education programs can be seen in; Caterpillar institutes Caterpillar University to create learning materials for existing or new employees. These companies have conducted hundreds of Six sigma training courses for its employees. Thus there appears to be a greater need for engineers to be educated with a strong understanding of Six sigma so they can then enter projects that enhance processes and reduce cost of poor quality from day one and on.

Many educators insist that Six sigma is an understanding of basic statistics to improve quality or a process. In turn, this basic understanding that is shown by the employees qualifies them to be put into high level Six sigma projects, [1]. The authors believe that the methodology in Six sigma is beyond basic statistics; one must also know the need for cost reduction in conducting experiments, the understanding of processes, design and manufacturing principles in a manufacturing related environment. Most importantly, these skills will not be gained from in class training via lecturing, exams, or homework. It is our belief the most effective training in six sigma is to incorporate lectures and hands-on projects to ensure that students are well equipped to not only conduct a project but also to be able to lead Six sigma projects.

For the past 4 years, the department of Industrial & Manufacturing Engineering & Technology (IMET), with CCET at Bradley University has delivered a six sigma course via lectures and homework on key six sigma tools and concepts. Further, lab-related lean projects, for teams of 2 to 3 students, have been developed to supplement the academic learning with hands-on experience. The IMET department hosts a lot of unique manufacturing equipment such as CNC turning center, CNC vertical center, 3D printing, Waterjet, or injection molding, all of which are designed for student use. Such lab-based six sigma projects guide students in reviewing the current quality condition in processes housed within our department. The goal is for the team to conduct a Six sigma project to optimize the process to enable enhanced quality from its current standard to at least a 4 sigma level.

The course has been well received by students and many graduates, most of whom have secured employment in the abovementioned companies. In the dynamic modern manufacturing environment, such lab-related and lecture-based Six sigma curriculum is a key component to opening students' eyes to the challenges facing a variety of industries, such as major organizational changes and global competition. In addition, every student in the team is required to lead the

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[1] http://www.cnbc.com/id/101373230

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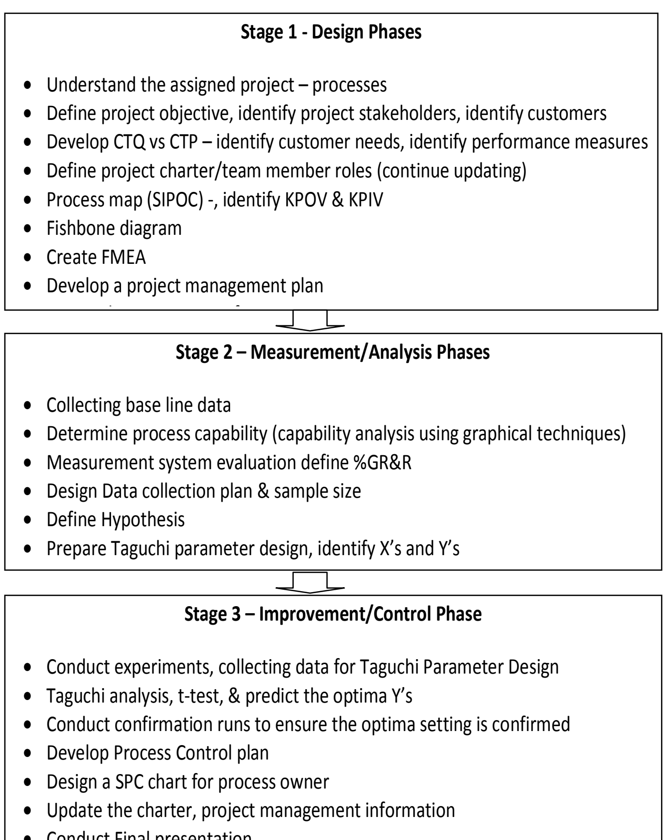
project, so they may further develop skills in leadership, teamwork, and project management throughout the course.

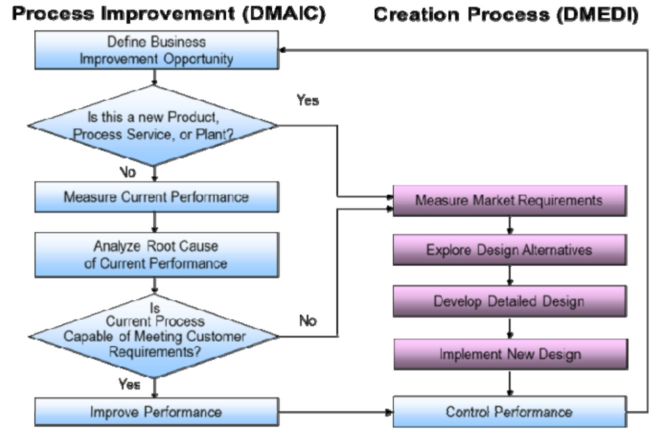
This paper attempts to share how more engineering educators can use a Six sigma hands-on curriculum so that their students are equipped with Six sigma methodologies. This should enable the engineers to be able to lead Six sigma related projects and contribute to industries right from the start of their employment. The organization of this paper is as follows: An overview of Six sigma is introduced in the next session. In session 3, the proposed Six sigma curriculum at Bradley University is discussed in detail, followed by a case study of a Six sigma project conducted in a 3D printing process which is a growing manufacturing technology. Finally, conclusions and discussions of future curriculum improvement strategies will be presented.

II. Overview of Six Sigma Methodology

Six sigma mythology consists of two categories, referring to Fig 1, The first process is to Define opportunities, Measure performance, Analyze potential causes, Improve performance and Control performance (DMAIC) for process improvement; and the other is to create new processes by Define opportunities, Measure market requirement, Explore design alternatives, Develop detailed design, Implement new design (DMEDI). This curriculum mainly focuses on DMAIC methodology.

Just from doing minimal online research it quickly becomes apparent that the DMAIC methodology has been utilized in a bevy of distinctive industries. For example, projects in the medical field where industrial engineers have implemented the DMAIC process to reduce patient waiting times like those seen in Applications of Lean Six sigma in an Irish hospital, [2]. Or the implementation of DMAIC tools for improving foundry flywheel castings like in, [3], to even researchers using it for improvement in LCD displays [4]. The need for





engineers to have a greater understanding of Six sigma projects is a growing concern for companies in any field of work. These articles really substantiate a need for more educational programs such as Bradley Universities Six sigma course.

III. The Six sigma Curriculum

This proposed three-credit Six sigma (DMAIC) curriculum (a total of 45 hours contacting hours) will be restructured into two major sessions:

1) 23 hours of lecture and lab activities for learning Six sigma DMAIC methodology
2) 22 hours working in a Six sigma project (2 or 3 students each) optimizing a process by producing a product.

The final result is an end-of-the-semester Six sigma presentation given by the team to the invited industrial mentors. It is our goal that the students will not only learn from their own Six sigma experiences, but also from the research of other teams' projects working in different manufacturing related focuses.

Fig. 1. Six sigma methodology (DMAIC and DMEDI)

Fig. 2. Three Stages of the hands-on Six sigma project

It is challenging for any instructor to teach a three-credit course of 45 contact hours consisting of theory and practical, hands-on experience, and although this curriculum was just only recently implemented, it is the authors' belief that there is room for continuous improvement.

The Six sigma project has been constructed with three stages, allowing different team members to rotate into the leadership position at each stage. This may mean that each team, in order to accommodate projects of different scale, may have a different scheduling (see Fig 2). At the end of each stage, the team submits its work for review, allowing feedback for improvement and adjustment as needed.

The instructor also develops rubrics for team members to evaluate one an others leadership and team work skills at the end of each stage. It is the instructor's hope that by conducting such a project, one has improved his or her leadership and teamwork skills. Such robust learning is very effective, yet time consuming. The requirements of each stage have been suggested to the students in such a manner that they do not to limit students' creativity into their recommendations for their industrial problems.

The following case study will provide detailed information of how such a Six sigma project has been conducted. This case study is one of the six team projects conducted in January 2014. Fig. 2 shows structure of the case study.

IV. Introduction to the Case Study:

According to [5], there is a global trend shifting towards 3D printing, where more industries are turning to this new technology for resolve. Students in this case study elected to examine the 3D printing process due to its growing popularity and strong ties to the manufacturing world. This case study will be divided into three sections where the DMAIC process is sub grouped into each of the following stages. For each portion of the DMAIC process just several of the tools students used will be presented in further detail.

Define:

In the first stage of the project, an in class lecture introduced each of the bullet points listed Fig 2. Students in this stage used the define tools known as the Project Charter and the CTC/ CTQ vs. CTP matrix as well as other instruments to describe where process improvements can take place. In this stage, specific focus will be given to the previously mentioned tools as they in essence capture the true meaning of the first DMAIC phase.

Measure and Analyze:

In stage 2 of the project, students were tasked with working through the Measurement and Analyze phases. These phases consisted of testing baseline capabilities of the process under review, forming a t-test hypothesis, and designing a taguchi orthogonal array. For the case study the baseline data will be explained and the design of the taguchi orthogonal array will be further described.

Improve and Control:

With the final stage of the project students had to complete the improvement and control phases. In these phases students needed to test the new optimal parameters found from the previous steps. After the improvement had been statistically proven, the control chart was designed to measure how well the process is repeating the results.

Forming a team:

Prior to undertaking any Six sigma project a cross-functional team must be formed with skills sets from across the company being combined to achieve a common goal. Successful teams should possess qualities such as, interdependence from member to member, advantageous risk takers, mutual trust while working in a relaxed climate, and defined roles so that little confusion is present. In our classes' case the teams were devised of 3 members so that rolls such as, project champion, master black belt, black belt, and green belt could be assumed [6]. These rolls allowed the student engineers to put thought into where they will have the greatest assets to offer the project and add value using their own knowledge skill set. In each group's case, teams were formed based on prior internship experiences, courses they had taken up to this point, and recognizable strengths that they could draw from. This in effect was done to simulate how a cross functional team would be utilized in any organization solving a six sigma improvement process.

1) Project Charter:

The first of such define tools introduced to engineers here at Bradley University is known as the Project Charter. When given the task of applying Six sigma methodology to a project, students had to find a clear direction from this document. The Project Charter in fact is a key deliverable document that helps in defining an issue a team needs to solve. When examining the pieces that make up the charter information such as; the objective statement or the root cause of the problem the team will tackle, the project scope which summarizes all the deliverables that add value, the business case which is the justification as to why a project has value to the sponsoring organization, and finally the benefit to the internal and external customers, will be mentioned. Using the 3D printing team as our example, they put together a full charter where their objective was to find the highest producing ultimate tensile testing parameters, while for the scope they would need the tensile testing machine, 3D printing machines and technical support to run the project. Additionally, the business case indicates a reduction in production cost by using plastics over expensive metals. Lastly the beneficiaries of this project were the IMET department of Bradley University whose students would receive insightful knowledge of Six sigma but also the plastics industry as a whole who gain valuable tensile strength data. From the Project Charter an overview of the 3D printing teams' mission was distinctly formed. This document gave structure and sustenance to how the rest of the project was to be carried out and the reason behind conducting this project in the first place. Furthermore, the Y of the problem or the objective of finding the ultimate tensile strength was decided upon.

CTP VS. CTQ/CTC					
	Strength	Toughness	Manufacturing Cost	Material Properties	Print Completeness
Machine Traveling Speed	⍰		▯	Δ	Δ
Infill Percentage	Δ	Δ		⍰	⍰
Layer Height	Δ	⍰	⍰		Δ
Mean Time to Failure	⍰	Δ	▯		
Dollar per Unit	▯		Δ		▯
Plastic Consumed	⍰	⍰	Δ	▯	⍰
Proportion of Resin in Filament			▯	Δ	
Averaged Number of Defects	⍰	⍰	▯		Δ
▯ = 1	⍰ = 4	Δ = 9			

Fig. 3. CTQ/CTC vs. CTP matrix

2) CTQ/CTC vs. CTP Matrix:

The second of such tools used in the define stage is called the Critical to Cost/ Quality vs. Critical to Product matrix. Essentially the basic function of the CTQ/CTC vs. CTP matrix is to take the newly defined Y, or the ultimate tensile strength, and evaluate all of the X's or process parameters that most significantly affect the tensile strength. Using Fig 3, it can be observed that the Y, strength, is listed in the first column, and the devised X's are in the following rows. Additionally, the shapes to the right of the chart have a corresponding value representing differences in a rating scale. These shapes are used to measure how important each X parameter is to the listed Y's. Placing a higher rated shape in a Y cell means that that X value or measureable parameter has a greater effect on the tensile strength or the other listed Y's. After the rating has taken place, the rows will be summed and the highest values should indicate which parameters should be used for further analysis. Looking more closely at the Fig 3, it can be observed that the first three parameters or X's listed, summed to have the greatest effect on the ultimate tensile strength. From this chart the 3D printing team was able to determine that machine traveling speed, plastic infill percentage, and layer height were the most significant factors when it came to producing the highest ultimate tensile tested part.

Once both the project charter and CTQ/CTC vs. CTP matrix were analyzed the following conclusions could be made. In terms of the project, the 3D team set out to find the highest strength parts, by using the IMET departments' 3D printers and measuring machines. Their idea was that the results of this test could be beneficial to businesses and the IMET department alike, in that they could provide detailed information on 3D printed products while using the DMAIC educational steps to achieve a goal. Moreover, from the CTQ/CTC vs. CTP matrix the team was able to further identify which specific parameters were deemed crucial to printing high strength parts.

3) Baseline Results

In the measurement phase, baseline data is tested and an initial idea about the capability of a process is formed. One of the specific tools used in this stage is known as the ANOVA gauge R&R measurement system analysis. The basic function of this tool is to assess a measurement instrument and the variance that the machine or user produce. This analysis made sure that the baseline tests were acceptable prior to conducting them. Once the 3D printing team had an acceptable measurement system, the baseline tests could begin.

For the baseline testing a small sample such as 10 parts should be produced and tested to find a processes current statistical capability. Factors like those identified from the CTQ/CTC vs. CTP matrix which included, layer height, machine traveling speed, and infill percentage should remain unchanged. This because these are considered to be the default settings or at least this was the circumstance in our teams study. The data represented in Fig 4, shows the current printing tensile strength when the parameters are left unchanged. From the baseline experiment, the mean strength is approximately 4500psi, with large deviations from that value. By the end of the measure phase, an understanding of a

Baseline Data

Area	Force	UTS (psi)
0.034336	159.7791	4653.399
0.035224	151.47188	4300.246
0.033726	165.22174	4898.943
0.0351	123.97216	3531.970
0.035264	171.2373	4855.867
0.035728	170.3779	4768.750
0.035343	167.79982	4747.753
0.034419	170.95082	4966.757
0.03503	171.2373	4888.304
0.03555	143.73759	4043.251

Fig. 4. Baseline data

processes current capability will be known and any additional conclusions drawn.

4) Taguchi orthogonal array

The next step in the DMAIC process, the analyze phase is used to understand a current process and test its variability though several advanced statistical tools. While conducting the Six sigma course students were introduced to the taguchi orthogonal array method. This is a tool engineers use to limit variation through robust design of experiments. When engineers begin to design the array for their own analysis they must decide on, which arrangement format to use, how many levels of the previously found parameters will be studied and if they want to include noise factors. The organization of the table is vital to the information it provides the engineers. In the provided Fig 5, a L9 format where 3 factors with 3 different levels of those factors were used for analysis. Included in the L9 design were also the noise factors, or those factors that may affect the results but are not the primary focus of the study. It can be observed that the 3D printing team believed that the extruded layer heights of .1mm, .25mm, and .4mm, a machine traveling speed of 100mm/sec, 150mm/sec, and 200mm/sec, and the percentage infill of 10%, 50%, and 100% were the primary levels that needed to be printed for testing. The teams array also encompassed two noise factors in which they had, printing with two different machines and in two different temperature zones of 45-50°F and 75-80°F. Upon completing the orthogonal array design, and the printing the specimens with the new parameters, the next stage of tensile testing could commence. Looking again into Fig 5, it clearly shows all the 72 newly tested tensile specimen and where they registered during the pulling process. Additionally, from the taguchi array a signal to noise ratio can be formed. The S/N ratio is a numerical value that indications how well the factors correspond to a desired signal, given the inclusion of possible noise. These values are used to help determine where the optimum parameters are located in the taguchi test for the desired Y variable, ultimate tensile strength.

After all the testing finished, the analyze phase was completed. In this stage the team was able to first find its baseline production capabilities. Then formulate new levels for selected parameters in order to test different specimen and find those that gave the highest result.

1) Confirmation Runs

In the improve phase all the factors that were evaluated from the analyze phase are put to the test in that they form the settings for the confirmation run. In this segment engineers must prove that the results collected will lead to the results they set out to find in the first place. From the analyze phase, printing on the lowest layer height at .1mm, having the machine move at its lowest traveling speed of 100mm/sec, and with the highest plastic infill of 100% lead to the highest ultimate tensile strength. Likewise, the t-test hypothesis found that printing in the warmer temperature and using machine one had an effect on the tensile results, thus they were used in the confirmation run as well. To validate the team's findings, 10 more 3D printed specimens were pulled using the above mentioned levels, and noise factors. Observing Fig 6, the results yielded a mean ultimate tensile strength value of 6389psi, with a corresponding standard deviation of 272psi. Given the outcomes in this phase of the DMAIC process, the 3D printing team could conclusively say that there was a rise in the ultimate tensile strength using the revised optimal parameters.

From the displayed results in Fig 7, three different levels used by the team during testing are presented. From the left two most parts, these were the weakest samples that were brittle in fracture and lacked tensile strength. The middle two parts were the baseline runs where fracture showed some consistency but little else, and the on the furthest right, these two pieces showed the improvement of the process where they had a consistent breaks and even fracture.

1) Control

In the final stage of the DMAIC process, the control phase is used to insure that a team's new found improvement will follow through the entirety of the six sigma process. The control phase is generally characterized by how closely a process follows standard operating procedure, where results will show limited variability and higher reproducibility. While our projects did not have the manufacturing plant setting, a reasonable production level estimate for groups could be assumed. This was to assure that the content of the control phase like the control chart was still made based on the specified requirements. By the end of this phase student engineers had designed a control chart that could easily be modified by the operator and allowed little confusion or room for error.

V. Conclusion:

Upon completing this project, student engineers were able to draw clear results of improvement using the specified tools

				Machine 1		Machine 2			
Run No.	Infill	Layer height(mm)	Speed(mm/s)	Cold Temperature (45-50)	Room Temperature (75-80)	Cold Temperature (45-50)	Room Temperature (75-80)	Y-bar	S/N Ratio
1	50%	0.1	150	6168.21	6324.77	6618.53	6563.86	6395.49	73.10
				6152.13	6576.86	6307.53	6452.00		
2	100%	0.25	100	5443.95	6419.99	6359.10	5738.69	6224.59	72.80
				6892.01	6534.48	6532.68	5875.86		
3	50%	0.4	100	5545.56	5148.46	4656.97	5339.69	5340.21	71.50
				5585.83	5519.24	5518.57	5407.37		
4	10%	0.1	100	5581.09	5923.76	5746.22	5717.43	5772.89	72.21
				5682.49	5887.94	5850.34	5793.88		
5	100%	0.4	150	4401.45	6402.65	4532.47	5697.60	5454.56	71.52
				5301.61	6152.90	5369.97	5777.87		
6	10%	0.25	150	5309.71	5526.02	5140.40	5238.56	5274.44	71.38
				5132.27	5641.85	4588.36	5618.37		
7	50%	0.25	200	5721.74	6416.76	6455.37	6297.23	6043.25	72.59
				6018.67	5842.10	5754.28	5839.85		
8	100%	0.1	200	6826.93	6854.22	7000.90	7024.76	6832.96	73.66
				6738.52	6788.48	6261.18	7168.69		
9	10%	0.4	200	3390.15	4065.38	3107.54	2099.92	3197.25	64.83
				3546.58	4411.49	1255.93	3701.00		

from the DMAIC methodology and following a Six sigma process. Using our case study of the 3D printing project, they were able to observe improvements in, mean tensile strength from 4565 psi to 6389psi, a decrease in standard deviation from 466psi to 272psi, and a Cp improvement from an assumed .75 to 1.08 . In total, a 40% increase in tensile strength was observed. This increase represented the largest possible tensile strength a 3D printed part can endure before it

Fig. 5. Taguchi array

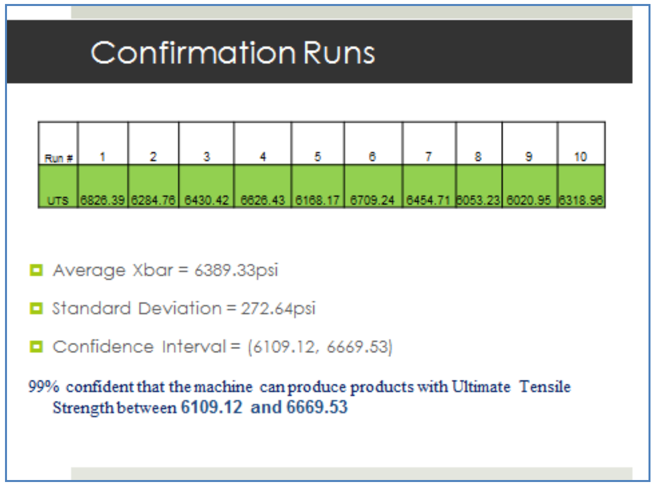


Fig. 6. Confirmation Runs

Fig 7. Displayed results from experimentation

reaches fracture stress. These results proved to be sufficient in that all the parameters studied covered a complete range of possible fracture stresses. Any organization reviewing these results could use this information to decide which parameters would best suit their individual tensile stress needs.

Students who successfully followed the Six sigma format were able to participate in a scaled down version of what they could expect to see upon entering a Six sigma project in the working industries [7]. Students also had a chance to deal with all the expected as well as the unexpected hurdles in this project. For example problems such as a parts sticking to the build plate, failure of the machine to extrude plastic, and jamming filament gave an even more realistic touch to every individual's project. This is important because having this back ground information to draw upon will not only allow our engineers to fully contribute to the industries improvement process projects but also give them a leg up on other employees who have not had the necessary experience or training.

As it has been stated from numerous online sources, the need for six sigma training is a growing concern for competitive industries in the global market place. We as educators believe there is a disconnection from educational institutes attempting to present the Six sigma methods and what is expected of engineers entering the work force. To address this disconnect, Bradley University has been implementing both lecture based and hands-on projects where machines in our facility have been utilized for a manufacturing simulation process improvement. By using the DMAIC process and a three stage project that incorporates the tools from each phase, is it our hope that Universities and Industries alike will make use of the information provided in this paper, while also recognizing the current educational benefits provided here at Bradley University.

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