

Design of Simple Multi-use Thermoforming Molds for the Beginner Machinist Designer

by

Shaka J.P. Thornhill

Submitted to the  
Department of Mechanical Engineering  
in Partial Fulfillment of the Requirements for the Degree of

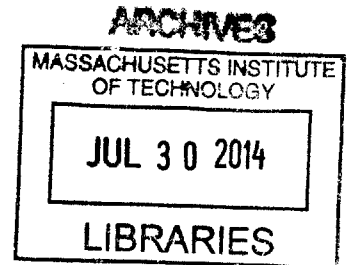
Bachelor of Science in Mechanical Engineering

at the

Massachusetts Institute of Technology

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## ABSTRACT

The aim of a class with Engineering Design points at MIT is to help the students learn how to put into practice different lessons and techniques in engineering a product. Beginner machinist are sometimes held back by the time consuming process of constructing proper housing in electronic dominant disciplines. The aim for this thesis was to devise a simple multi-use molding system to facilitate learning for the beginner machinist.

Five schemes were used in conjunction with seven shapes and sixteen different detail designs to come up with thirty seven molds, out of the five hundred and sixty mold possibilities, which students may use in multiple ways. Choosing Renshape<sup>®</sup>5025, a polyurethane based thermoset foam for the mold material, allows the limited facility in the EDS lab to repair and manufacture a variety of mold designs. With the addition of plywood base board for added weight and grip ensures that the forms are easily removed without damaging the molds.

Thesis Supervisor: Steven B. Leeb

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## **1. Introduction**

MIT students learn through many classes the theoretical approach to building mathematical models of their ideas. Courses like Microcomputer Project Laboratory, 6.115, and Power Electronics Laboratory, 6.131, offer hands on approach to teaching the students how to manifest their ideas. In the Electrical Engineering and Computer Science discipline, an introduction to the machines and tools used to build physical prototypes and manufacture goods are not an early focus in the curriculum. If the students have a lab equipped with ready to use molds to make casing for alarm clock or mp3 player dock that they designed then this will be beneficial. This will allow the students to focus more on the Electrical and Computer Science component and less on the machining. Furthermore with a class as large as 80 students, thermoforming molds would be cheaper and faster than most other forming methods. Appendix A shows 43 mold designs that when used together allows the student to do just that. Making it easy to create a case for the iPod or cover for a speaker.

## **2. Thermoforming Basics**

There are many ways to manufacture goods but since the invention of motorized vacuum pumps in the 20<sup>th</sup> Century, engineers started playing with thermoforming. Although new techniques and materials have been found over the years, the basic process is still the same.

## 2.1. Mold Creation

### 2.1.1. Mold Design

First the decision for a male or female mold is decided. Both mold options are shown in figure 1. This is usually determined mainly by end shape. Both molds forms leave the top portion with a thicker layer of plastic<sup>2</sup>. Depending on which side of the form requires more strength can influence the choice of male or female.

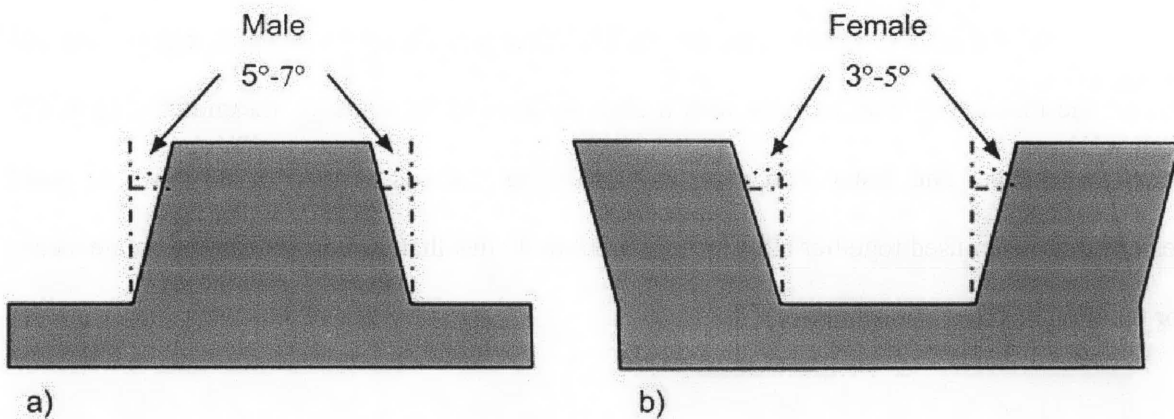


Figure 1: a) Male mold with suggested draft angles b) Female mold with suggest draft angles<sup>2</sup>

### 2.1.2. Mold Criteria

For a form to be made properly three things need to be in place. First is the draft angle, which is a slight angle of vertical surfaces to help the form release from the mold. This is because most materials used in thermoforming shrink. Because most molds are meant to be reusable draft angles make it possible to separate mold from finished form without damaging either. Second is a Base plate. This ensures that the plastic does not total encase the mold on the 6<sup>th</sup> surface and allows the mold to be released from the form. Base plates can also add weight to the mold to

allow for easier release. Last is the relief hole. Air can be trapped in pockets between the mold and the form. These holes allow the removal of air pockets to let the form fully conform to the mold.<sup>2</sup>

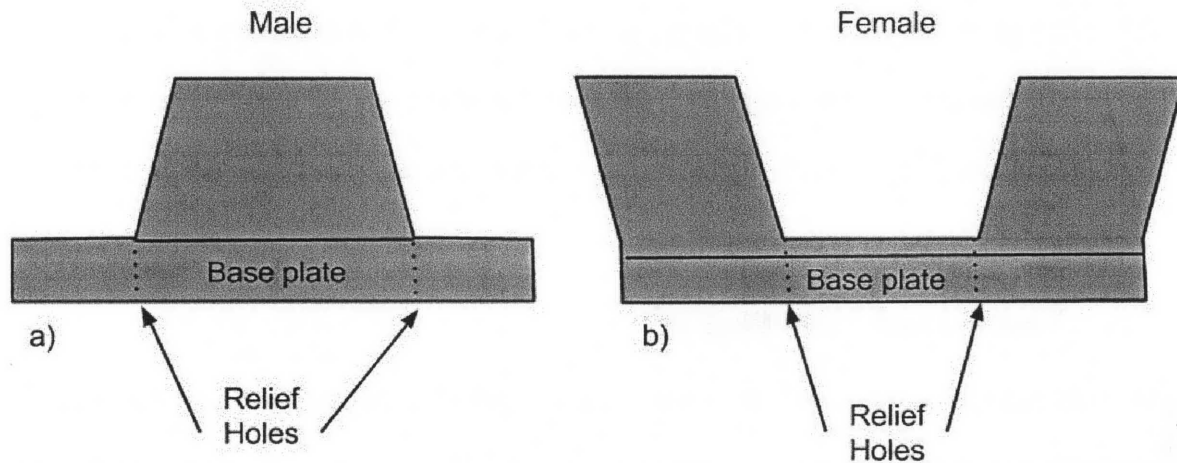


Figure 2: a) Male mold with relief holes and base plate b) Female mold with relief holes and base plate

## 2.2. Material Clamping

After the mold has been constructed, a sheet of forming material is secured in place. This clamping also creates a seal for the vacuum to function. The frame of the clamp needs to be strong enough to ensure the sheet is held firmly while resisting the vacuum pressure. Additionally, it must ensure that it can be adjusted to the different thickness and dimension of the sheet.

## 2.3. Material Heating

A heat source is placed over plastic to the point of phase change from solid to liquid. In order to get best results, heating should be done uniformly over the entire sheet and through its thickness. Most vacuum formers have variable zones that can be customized to best match the dimension and thickness of the sheet material. Overheating the sheet material can cause webbing and other

deformities. Under heating can cause decrease definition of the mold. Heat time is complex to predict and so some trial and error is need to find the appropriate heat time

#### **2.4. Material Pre-stretch**

When the plastic is ready for forming, it can be pre-stretched to ensure a more even wall thickness when the vacuum is applied to the mold. Pre-stretch can be useful when drawing parts with more depth. This is usually performed by a release of compressed air under the sheet.

#### **2.5. Vacuum and Mold Plug**

Once the material is pre-stretch, the vacuum can be applied to sheet to form over the mold. Some machines us two stage vacuums to ensure the rapid molding of the heated material. Mold Plugs are optional and can then be used to help further form the sheet to the desired shape. Plugs are usually used when forming multiple impression male molds as they can be situate near each other without the worry of webbing.

#### **2.6. Form Cooling and Release**

Once the sheet is formed, it must be allowed to cool before being release from the clamp and the mold. This can be helped by forced cooling with a powered device spraying mist on the mold or by applying a damp cloth. If the sheet is released too soon it will warp and deviate from the intended shape



## **2.7. Form Trimming and Finishing**

Now that the sheet is formed, cooled and removed from the machine, excess plastic can be trimmed. Holes, slots and cut-outs can then be performed to get it to the desired final shape.

## **3. 3D printing Comparison**

Additive Manufacturing methods are very capable to make a variety of complex and simple shapes or objects. It also is not limited in the forms that can be made when compared to Thermoforming. The EDS lab only looked at one other option beside Thermoforming and that was 3D printing.

### **3.1. Cost**

The price of 3D printing material is anywhere from \$20-\$180 per kg dependent on the color and type of plastic<sup>1</sup>. Comparing this to the price of Sheets of plastic for thermoforming, which range about \$1-\$10 per kg, we can see one of the drawbacks of the materials of 3D printing<sup>4</sup>. Additionally the cost of industrial thermoforming can range from \$5,000-\$20,000<sup>2</sup>. 3D printers have dropped in price to about a few hundred dollars but these have a very limited foot print. In order to ensure breath of scope for size a larger more expensive model would have to be used and with prices ranging upwards of about \$10,000+<sup>1</sup>.

### **3.2. Utilization**

The second factor we compared was utilization. Table 1 gives a breakdown of the utilization that we can expect in a conservative class with 80 students, lab only open from 9-5pm on weekdays and only one project to do the whole semester.

**Table 1: A utilization breakdown of ideal project cycle with weekday 9-5 access to lab.**

Utilization Table						
# of Students	80					
length of Project	3	Months				
Lab availability for	52	Hours / Month				
	Job completion range		Utilization w/1 machine			Optimal
Method	Low	High	Low	High	Avg.	Stations
Thermoforming <sup>1</sup>	0.5	3.0	26%	154%	90%	1
3D Printing <sup>4</sup>	8.0	24.0	410%	1231%	821%	9

As can be seen from the table you would need nine 3D printers to get close to the same utilization of one vacuum former. This information further supports our chosen forming method.

## 4. Method of Mold Design

### 4.1. Shape Factors

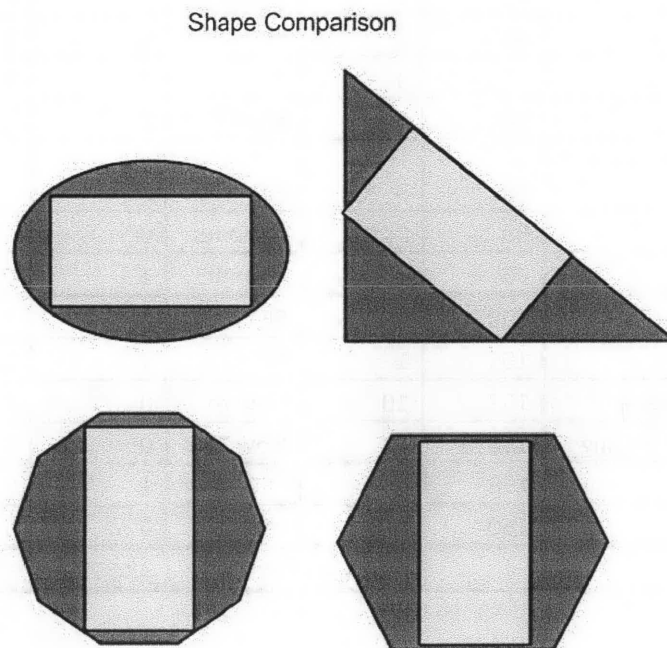
The first determination of mold design is the shape of the mold. Research was done mostly by analyzing project suggestions in Maker Magazine. Table 2 is a breakdown of sample data taken from the magazine.

**Table 2: Sample projects with some significant criteria found. Total is for all projects classified from issues 1-34<sup>5</sup>**

Name	Page	Volume	Principles	Complete Casing	EE Focus	Both
Desktop Rail Gun	12	1	Physics	0	0	0
Glowstick A Go-Go	34	1	EE	0	1	0
MOD your ROD	49	3	EE	0	1	0
Kite Aerial Photography	50	1	MechE	0	0	0
Halloween Haunted House Controller	86	3	EE	0	1	0
Lego Soccer	88	6	Robotics	0	0	0
Mousey the Junkbot	96	2	Robotics	1	0	0
Gun-Controlled Alarm Clock	100	8	EE	0	1	0
Magnetic Stripe Reader	106	1	EE	1	1	1
Electronic Test Equipment	158	10	How to	0	0	0
Microcontroller Programming	158	4	How To	0	0	0
Midi Control	158	7	EE	1	1	1
Moldmaking	160	8	MechE	0	0	0
			All Issues Total	38.30%	31.91%	19.15%

Complete Casing is set as “1” if the project was completely cased. EE focus is set as “1” if the project’s main principle discipline was Electric Engineer. As can be seen by the results only about 38.30% were completely enclosed. Of the total “Complete Casing” close 50% of them were EE focus. This leads to evidence that the Shape of the casing can almost be entirely determined by the electric circuit board on the inside. This let us know that we can have the best success of having a set of mold be useful for a variety of situations if they can meet a few

criteria. One is that the case totally encloses the standard circuit boards use by the lab. Extra space can be added in case of wiring, capacitors and other components. Next criteria is that since most circuit boards are four sided then rectangle/squares will be the dominate shape needed. Another criterion that becomes obvious is that more shapes will be needed to cover additional creativity. But these less dominate shapes can't deviate too much on the # of sides as when we deviate from four sides we end up with more wasted space. This is visually shown in fig. 3 giving reason not to deviate more than  $\pm 2$  sides beyond 4.



**Figure 3: a) Shape Comparison with red representing space with high probability of not being used.**

## **4.2. Detail Selection**

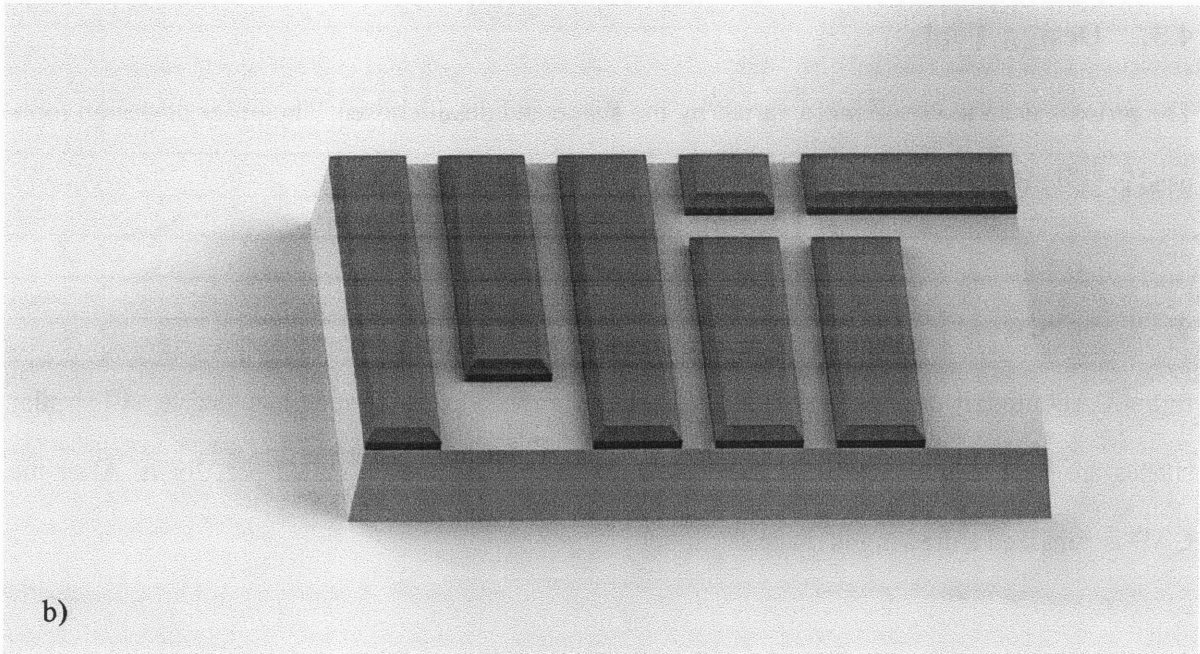
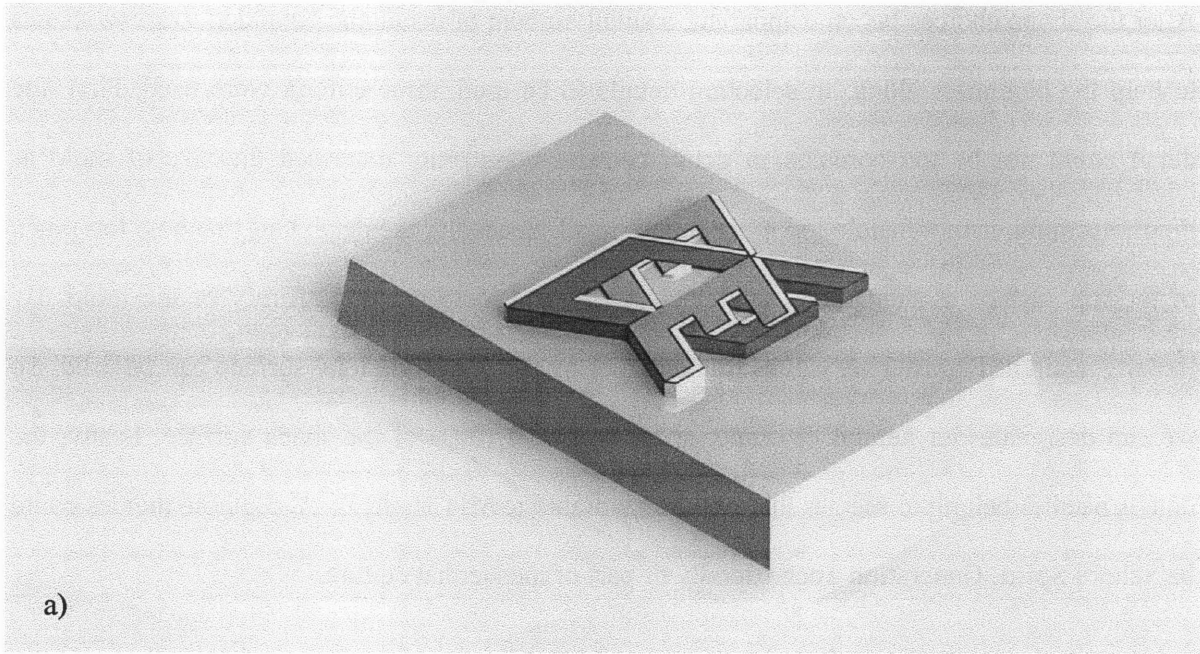
After the shape choices become apparent, a small amount of detail can be added to some shapes to help the beginners along. In selecting details to be used, three criteria were used. First, the detail could not be too complex in detail because complexity increased the size of mold as thermoforming cannot handle too much small detail. Secondly, the detail can't take up too much of the top surface as this might restrict creativity and multi-purpose affinity of the mold. By looking again at Figure 3 we can estimate that at most 50% of the total surface can be used. So we can designate our neutral or empty space to be 50-100% of the shape surface. Lastly, the details need to belong to themes that will be favorable to MIT students. Acceptable themes could be School Spirit, Generation Tech friendly or part of the Nerdist culture.

## **4.3. Design Tools**

The process used to create mold varied by the shape and detail chosen. The order of design tools used is fairly consistent even with the variations.

### **4.3.1. Solidworks**

Initial CAD models of chosen shapes and details are made to the correct perspective. All similar shapes are kept to the same base dimension for ease of building a mated part for it. After the CAD is finalized a drawing is made of model.

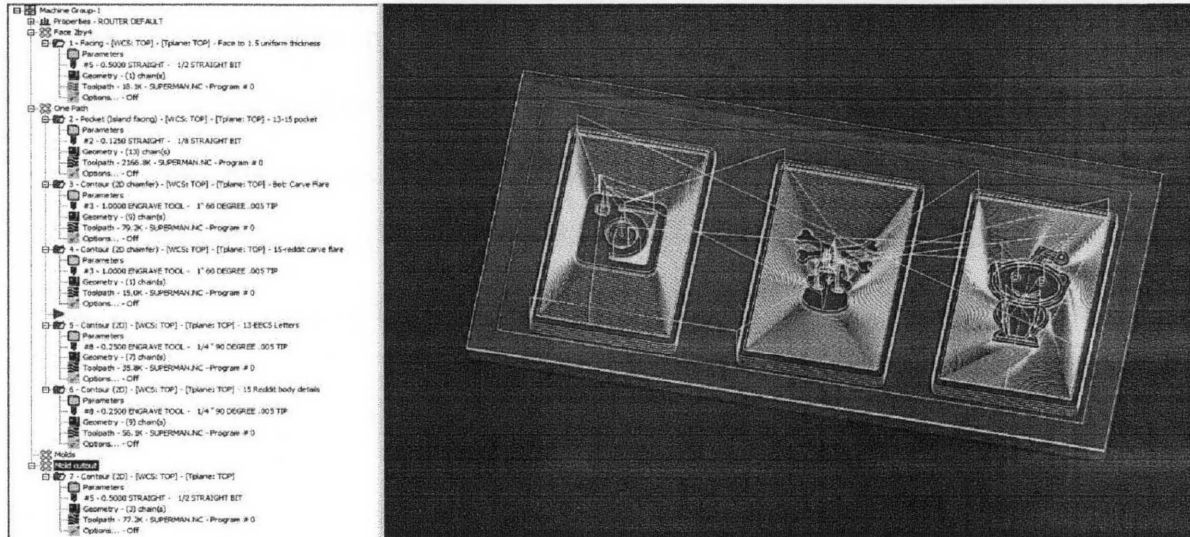


**Figure 4: a) rectangle shape with EECS logo b) MIT logo with same base dimension as part a. Both use the same baseplate and need the same mated part.**

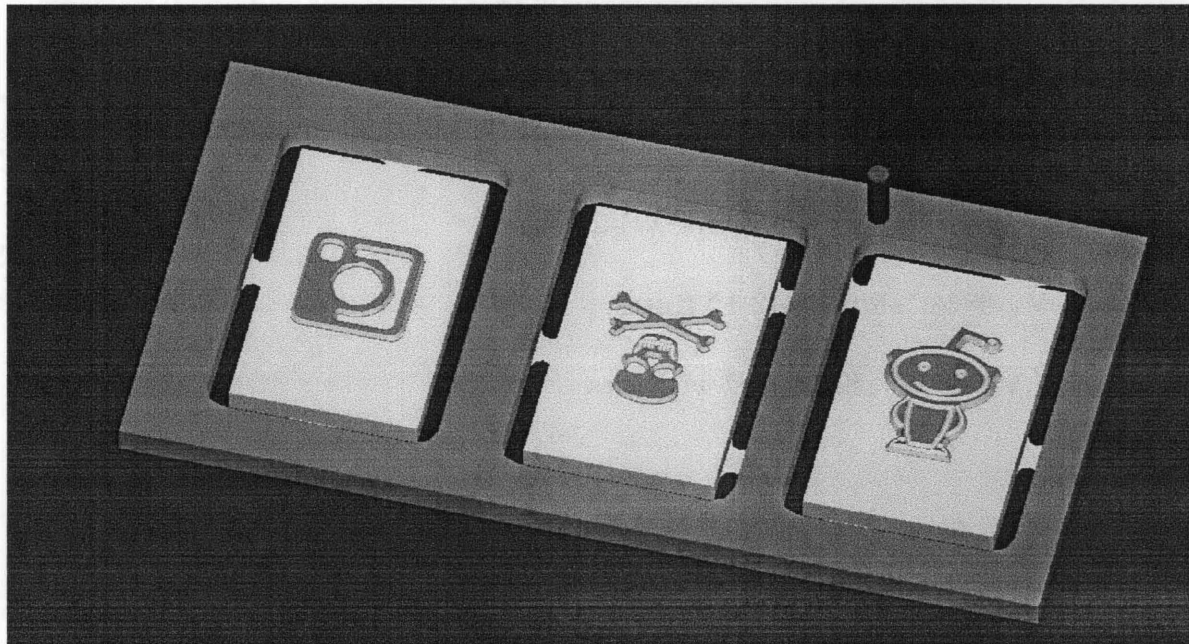
### 4.3.2. Mastercam X6

The drawing file is then imported into Mastercam X6. Here tool paths are constructed in Figure

5. The tool paths are then check visually with a computer simulation as can be seen in Figure 6.



**Figure 5: Sample constructed tool path done in Mastercam X6. Left are the tools chosen with their respective path type. The right shows the predicted movement of the tools.**



**Figure 6: Simulated outcome of constructed tool path to visually check for mistakes in tool movement.**

Once the tool path is verified the G-code is generated to use with a CNC machine.

### **4.3.3. Router (Techno or Shark pro)**

The G-code is loaded in to a router to do the rough cut of the mold shapes. Most detailing is done here also to ensure the detail is placed correctly on the mold. Several router bits are used in this stage. The material is first faced with a 2.5 facing bit. Initial cuts and outlines of the detail is done with the 1/8" and 1/4" straight bits. The chamfers and finer detailing is done with the V-60° and V-90° bits. Finally the rough mold is cut out of the material with the longer fluted 1/2" straight or 3/8" spherical bits. The base plates are also cut out at this point

#### **4.3.3.1. Router Bit List**

- a) **2.5" Face bit 1/2" shank w/2 3/4" flutes**
- b) **1/8" Straight bit 1/4" shank w/2 1/2" flutes**
- c) **1/4" Straight bit 1/2" shank w/2 1/2" flutes**
- d) **1/2" Straight bit 1/2" shank w/2 1.5" flutes**
- e) **3/8" Spherical bit 1/2" shank w/1 2" flute**
- f) **1" V-60° 1/2" shank w/2 1" flutes**
- g) **1/2" V-90° 1/2" shank w/2 1" flutes**

#### **4.3.4. Hand and Belt Sanders**

The rough molds are not sanded to remove any flash or burs. Non-straight edges are finish here by using the sander at a 7° angle to apply an initial draft. This is follow by hand sanding with



papers and files to smooth out the drafts and remove any burs in the detail. At this stage the base plates are also sanded by the hand and belt sanders to remove any burs from the material

#### **4.3.5. Table Saw**

The last design tool is a table saw. A flat edge jig is made to facilitate cutting a 7° draft angle on straight edges. This jig allows a consistent draft to be made with minimal effort and maximum safety.

#### **4.4. Material Selection**

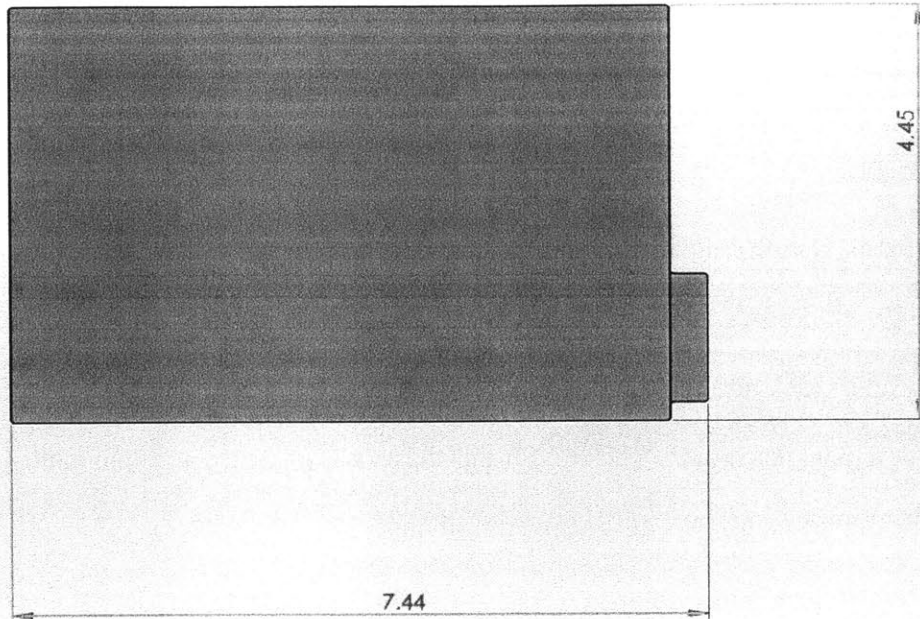
Choice of material of Mold had a few top choices. Aluminum was foremost of options for the mold but due to the restrictive availability of machining tools in the EDS lab it was not used. One goal was to have the molds easily repaired and/or remade from scratch. To use Aluminum as a material the lab would need a CNC milling machine at a minimum. The only CNC machine in the lab was a router. With this in mind a polyurethane-based thermoset foam board was used called Renshape® 5025. The price of Renshape per kg is slightly higher but, with its machinability being better than wood, made this the perfect choice. The base plates were also not made out of Aluminum for the same reason as the mold. Weight and durability were the main factors in this part so wood was chosen. Ply would seem to best fit the need so a no gap Luan plywood was used to keep the structural integrity of the base in a vacuum.<sup>6</sup>

#### **4.5. Quality Control**

Quality control was performed once the machining process was complete. Step 1 involved the use of a Caliper to verify the critical dimensions. The critical dimension depends on the stock shape of the mold. This ensures that all similar shapes would be of the same dimension and could therefore reduce the number of configurations of bases that needs to be prepared for the form. Step 2 of quality control was to use an Angle Block to verify the 7° Draft for easy release. If either step failed by more than 5% accuracy the mold would be sanded by hand till verification was met.

#### **5. Mold Design**

The molds that will be used in the EDS lab had to have the capacity to fit a circuit board made for the project classes that are being held there. Figure ##### shows a solid work sketch of the dimensions of the EDS lab Custom circuit board or EDS-board.



**Figure 7: Dimensional Schematic of Custom Circuit Board made for EDS lab (EDS-board).**

With this as the main criteria for restrictive dimensions, 5 Circuit schemes were formulated and are reflected in the naming schemes of all drawings in Appendix A. 0C is for any mold that the EDS-board would not fit. This was chosen to accommodate small independently chosen boards like some of the popular microprocessors (i.e. Arduino.) The 1C scheme is designate for any shape that can comfortably fit one EDS-board. 2CP is the designation for a mold that can hold two EDS-boards arranged in parallel to each other. 2CS is the designation for a mold that can hold two EDS-boards stacked one on top the other. Finally 4CSP is the scheme that can hold 4 EDS-boards in a 2x2 stacked formation. These 5 Schemes, combined with 7 choices shapes and 16 different Details are used to make over 30+ different molds.

## **6. Conclusion**

The aim of a class with Engineering Design points is to help the student learn how to put in to practice different lessons and techniques in engineering a product. Beginner machinist are sometimes held back by the time consuming process of constructing proper housing for electronic dominant disciplines. The aim for this thesis was to devise a simple multi-use molding system to facilitate learning for the beginner machinist.

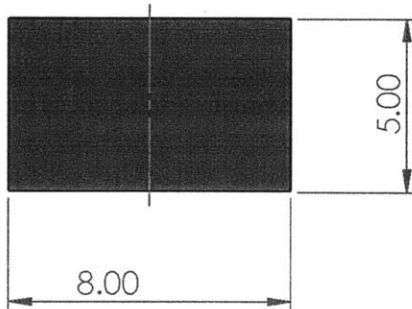
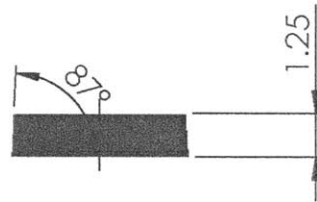
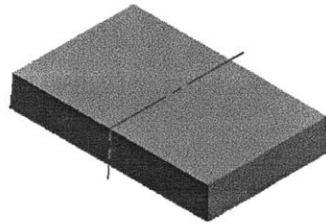
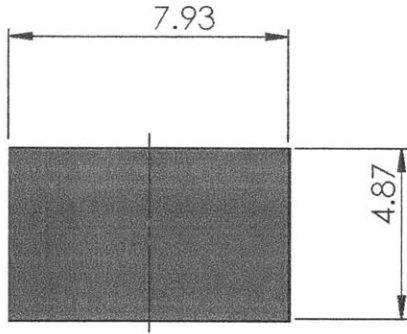
Five schemes were used in conjunction with seven shapes and sixteen different detail designs to come up with thirty seven molds that students can use in many different ways. Choosing Renshape<sup>®</sup>, a polyurethane based thermoset foam, for the mold allows the limited facility in the EDS lab to repair and manufacture a variety of mold designs. With the addition of a plywood base board for added weight and grip, allows the forms to be easily removed and reuse the molds.

In the future if a CNC mill is ever added to the Lab, The molds can be easily remade and maintained in Aluminum using the G-Code already generated. Wood can also be used to remake molds but its machinability is not as good as that of the foam but its durability is better for a longer lasting mold core.

## 7. References

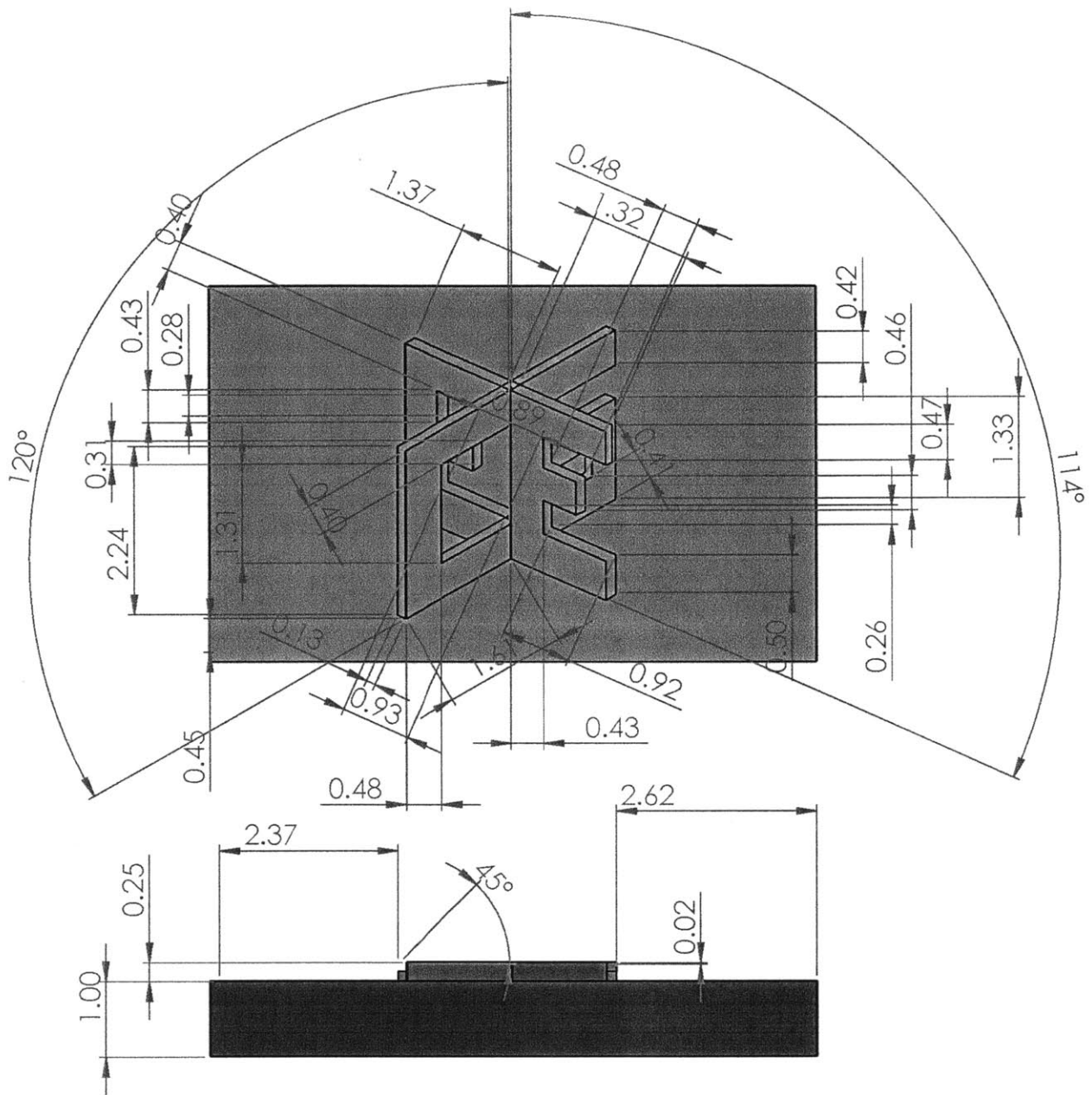
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**Appendix**  
**Appendix A: Model Drawings**

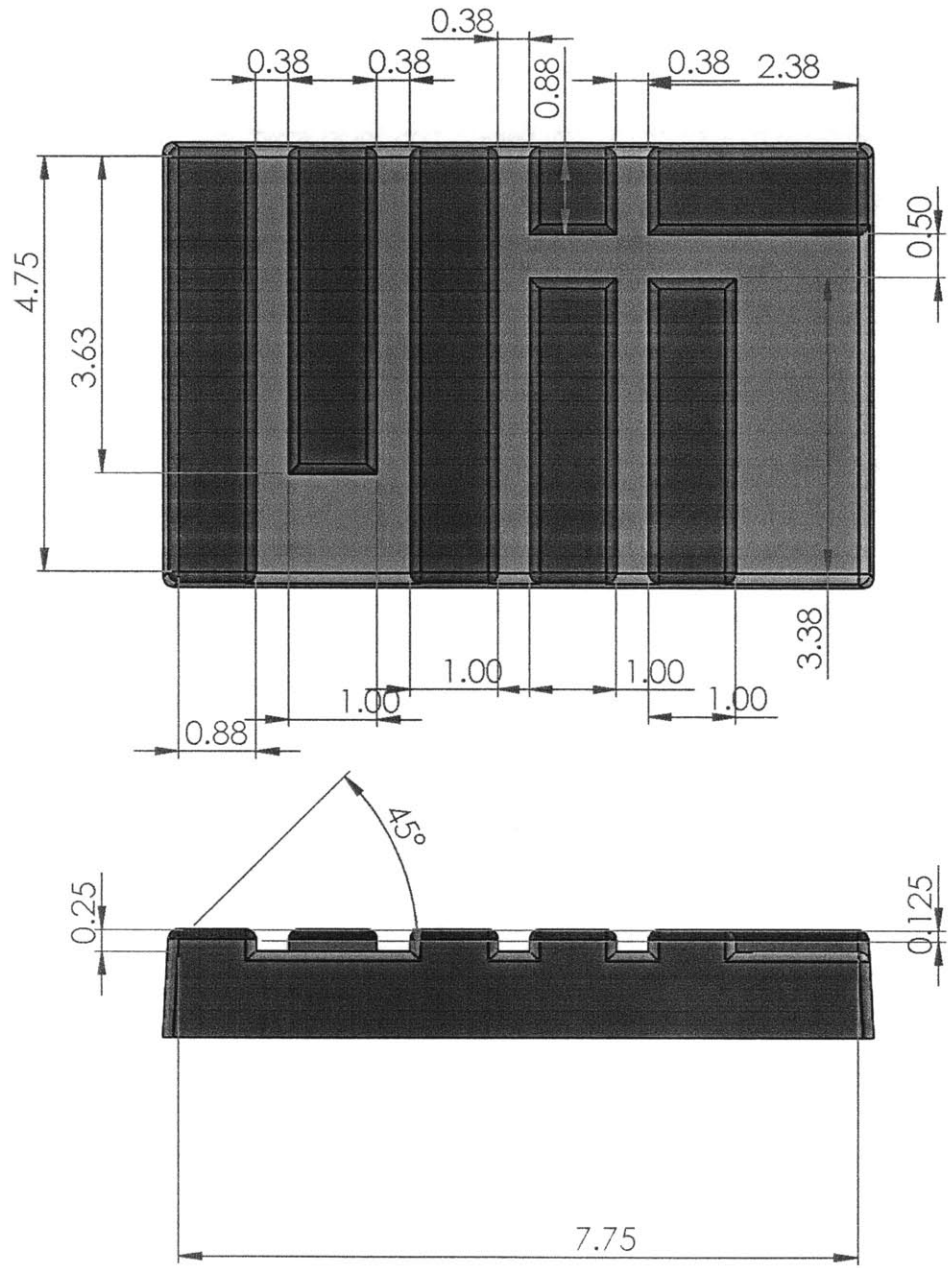


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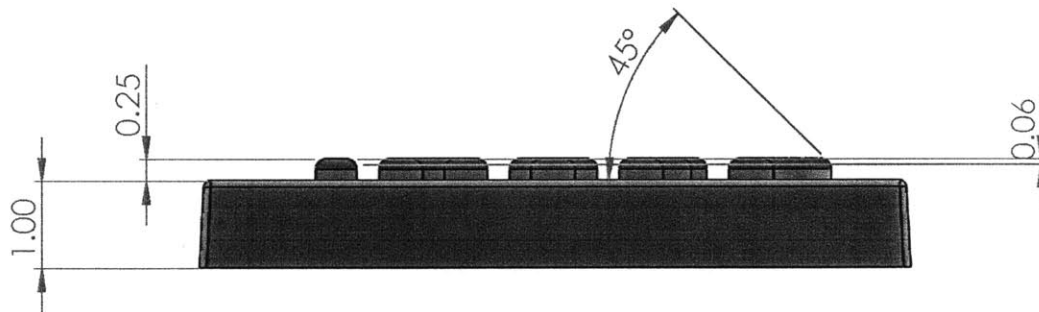
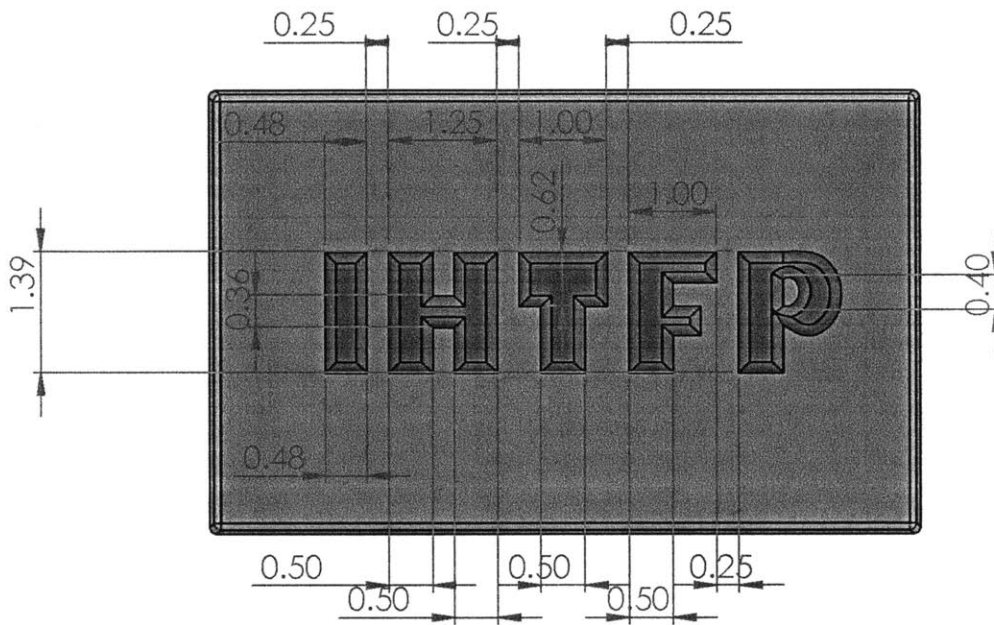
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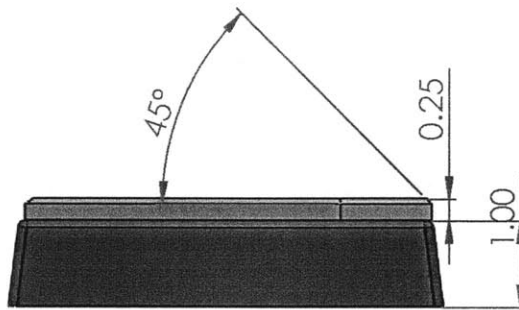
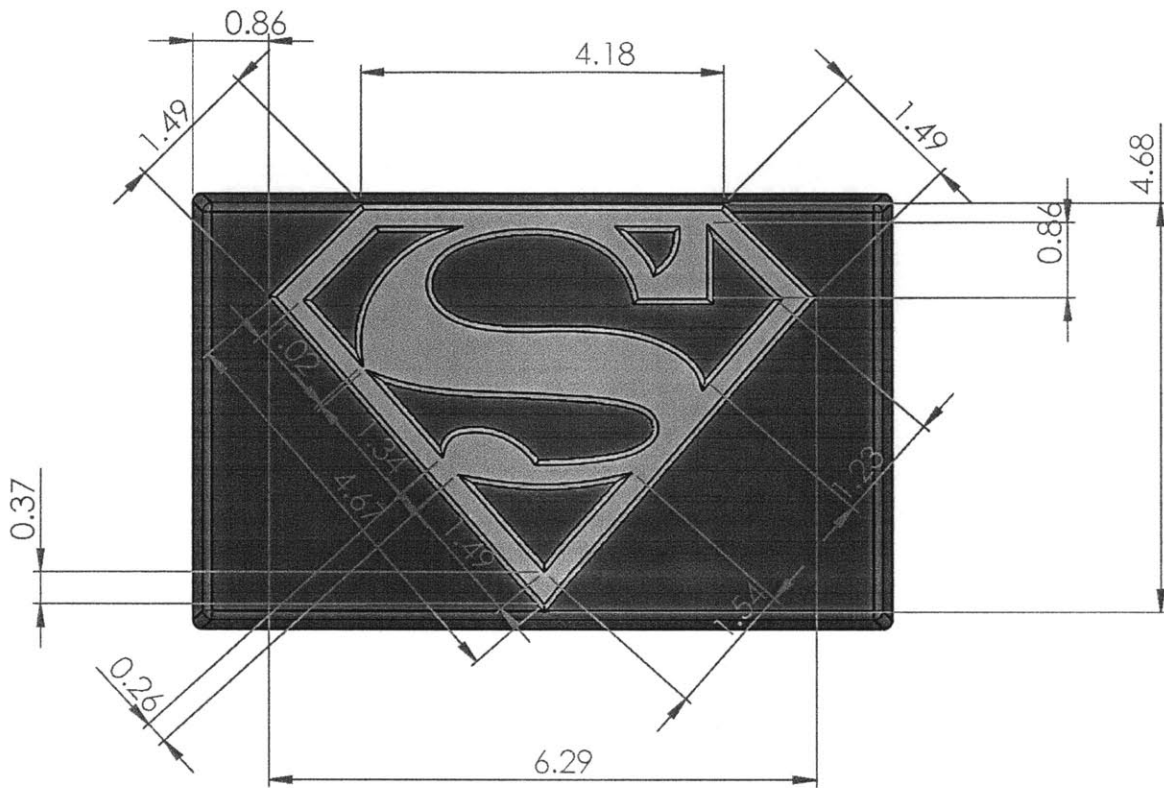
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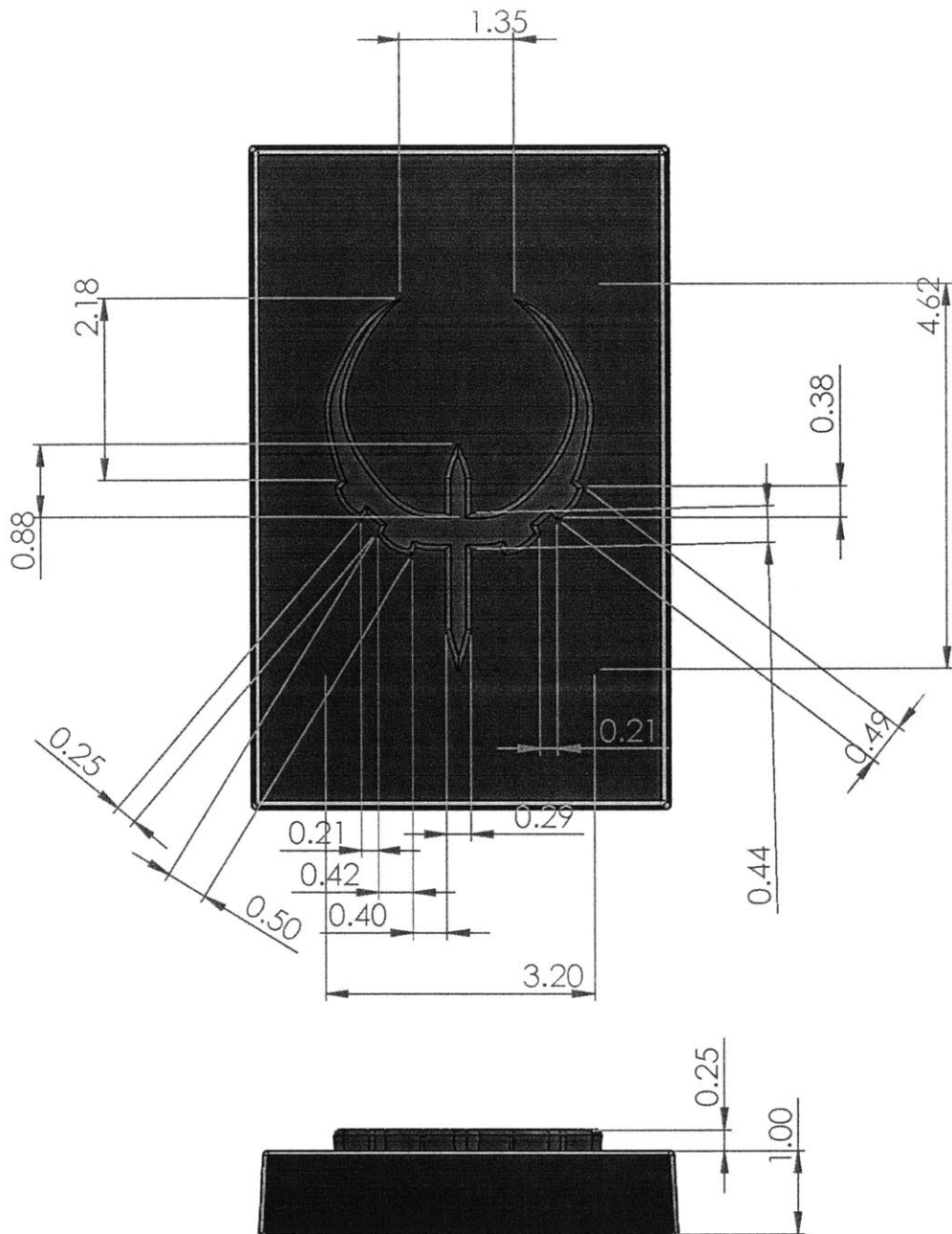


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WEIGHT:				SCALE:1:5	SHEET 5 OF 43	



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 LINEAR:  
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FINISH:

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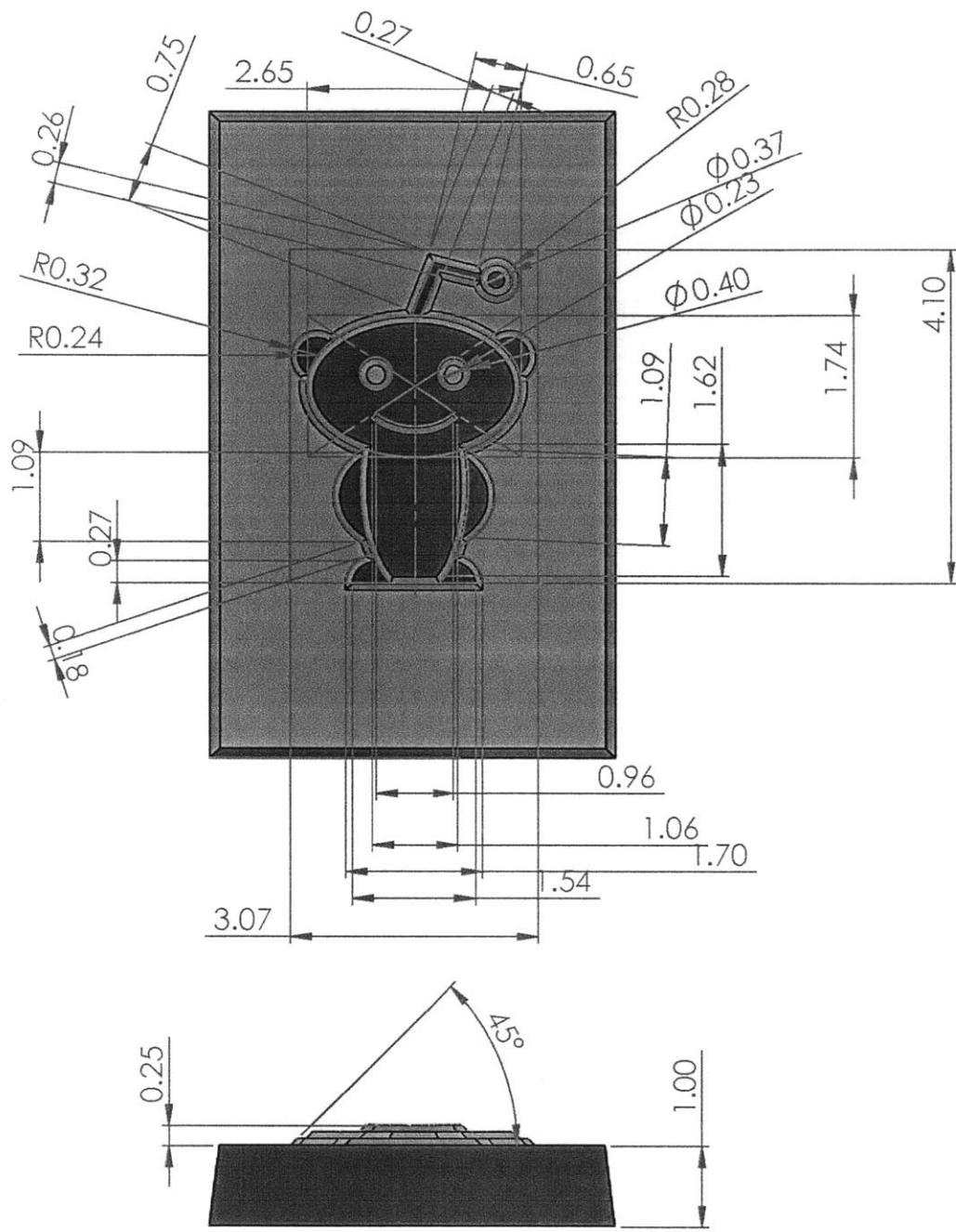
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**Quake-1C**

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31



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FINISH:

DEBUR AND  
 BREAK SHARP  
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REVISION

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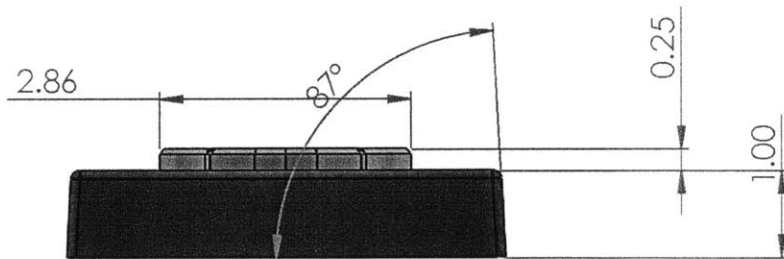
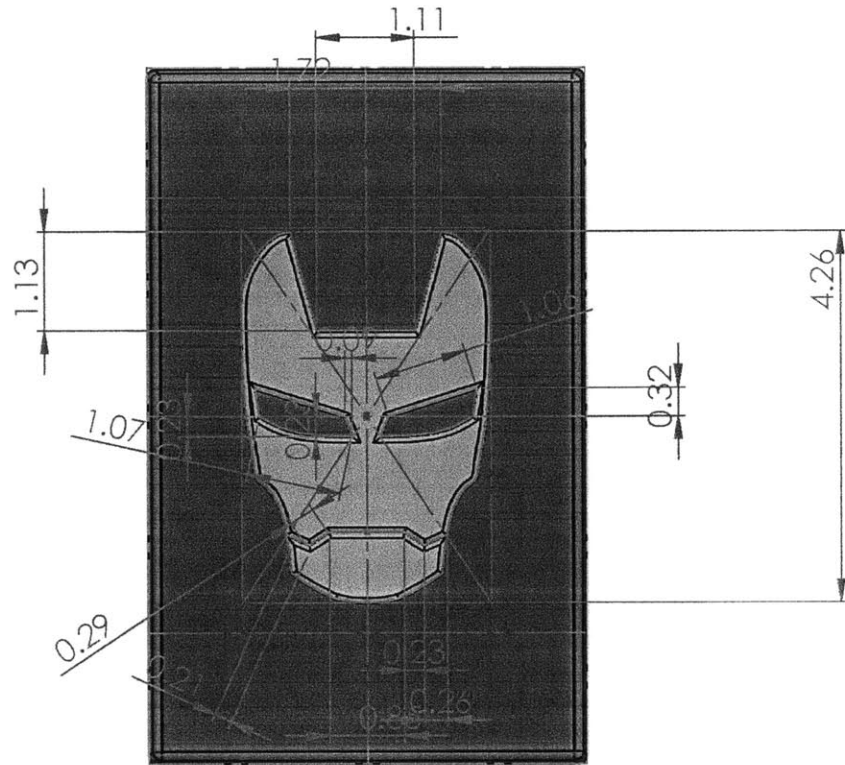
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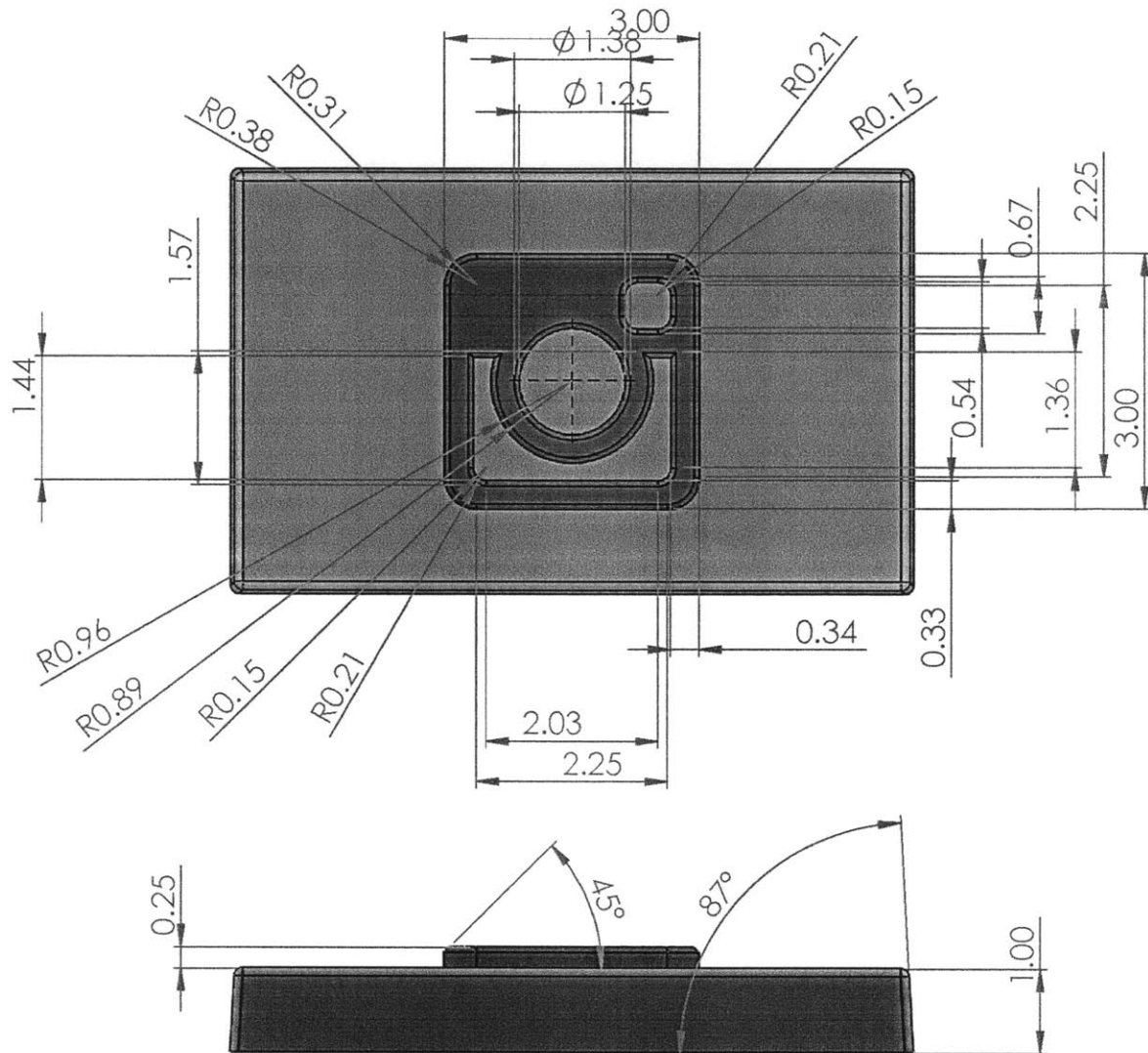
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SHEET 7 OF 43



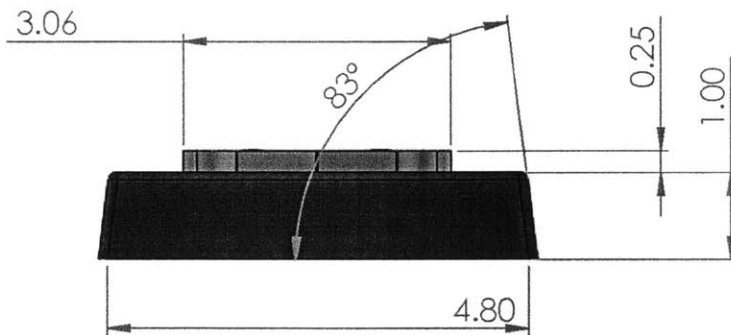
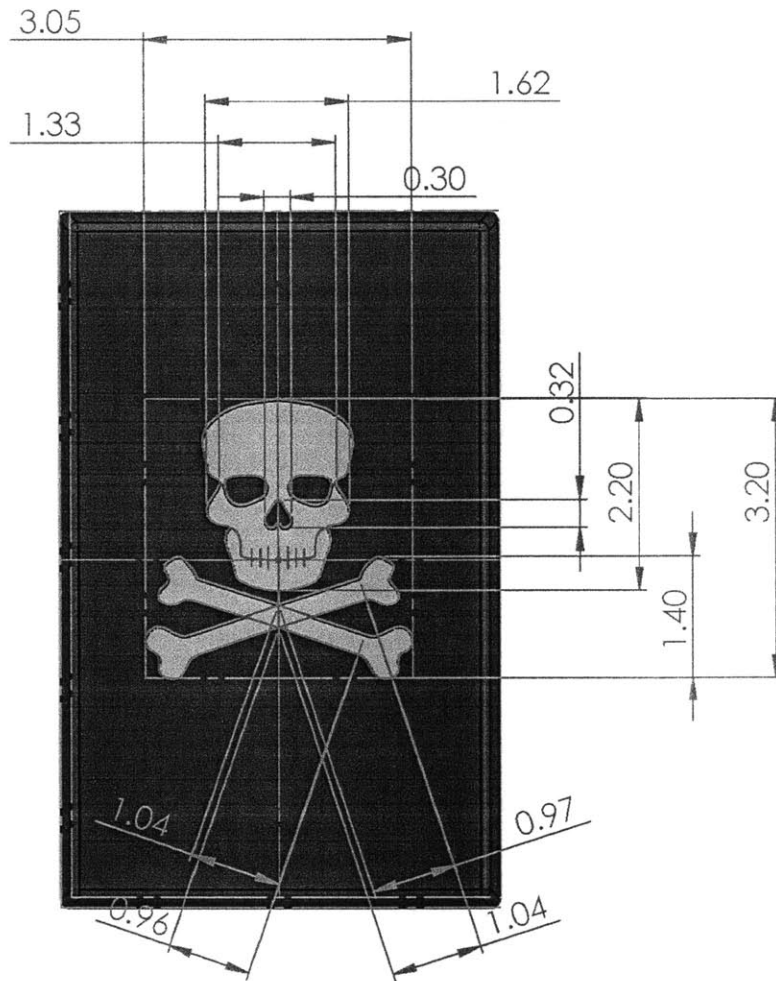
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						Ironman-1C		33	
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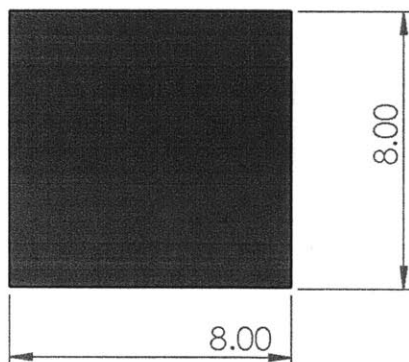
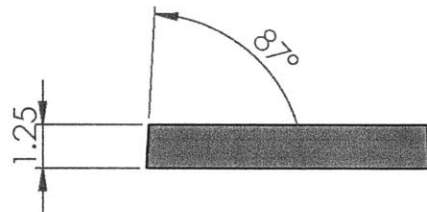
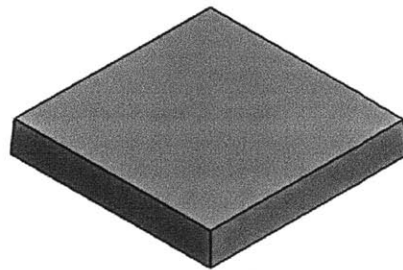
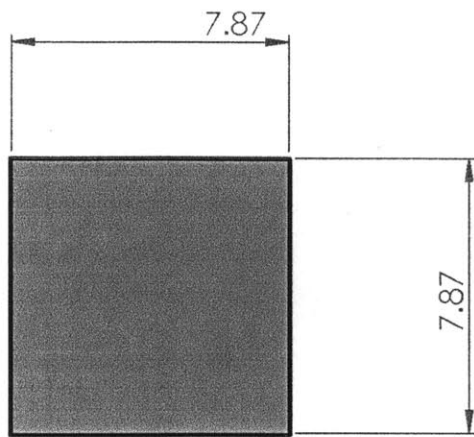


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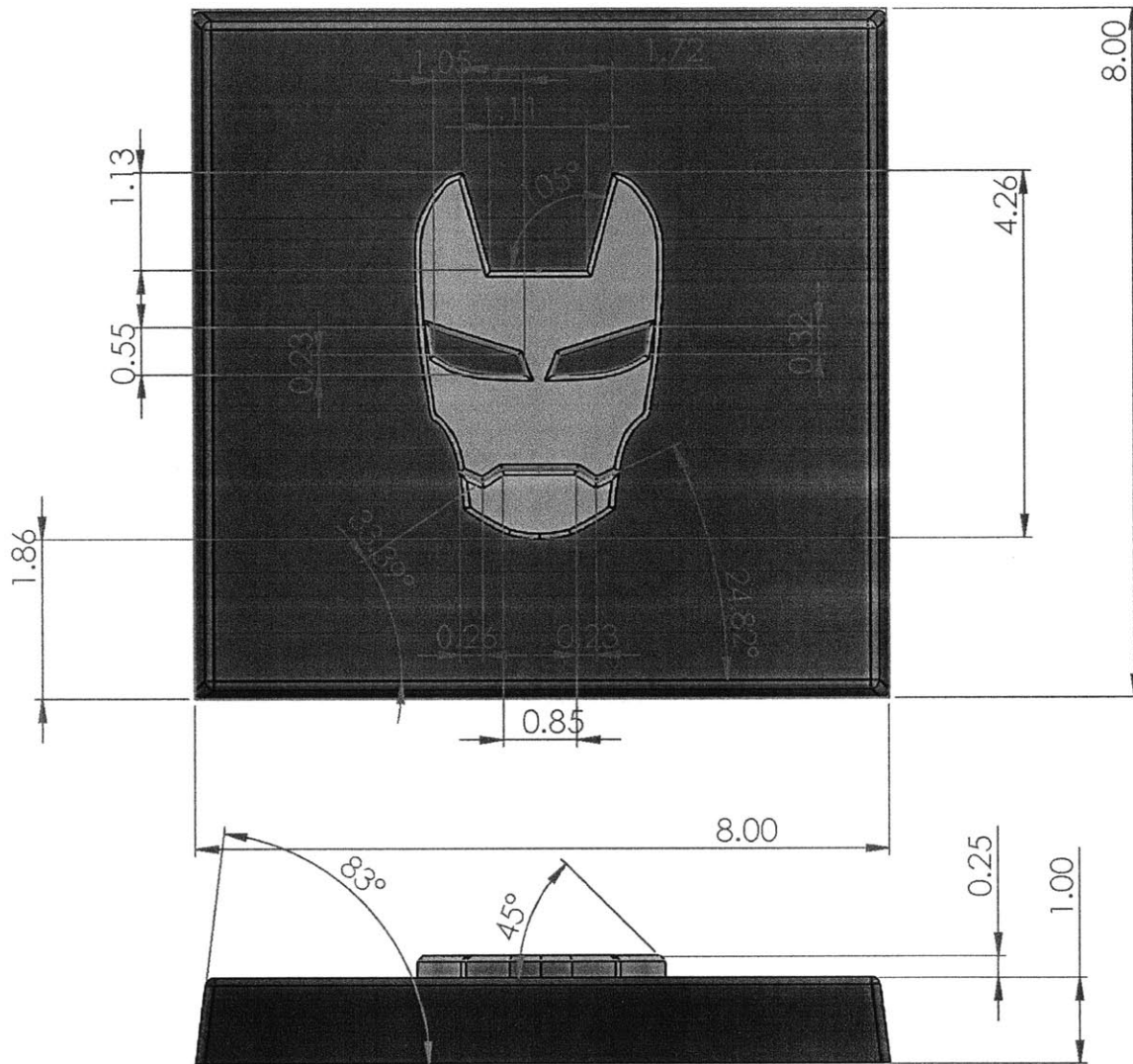
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**Ironman - SQU-1C**

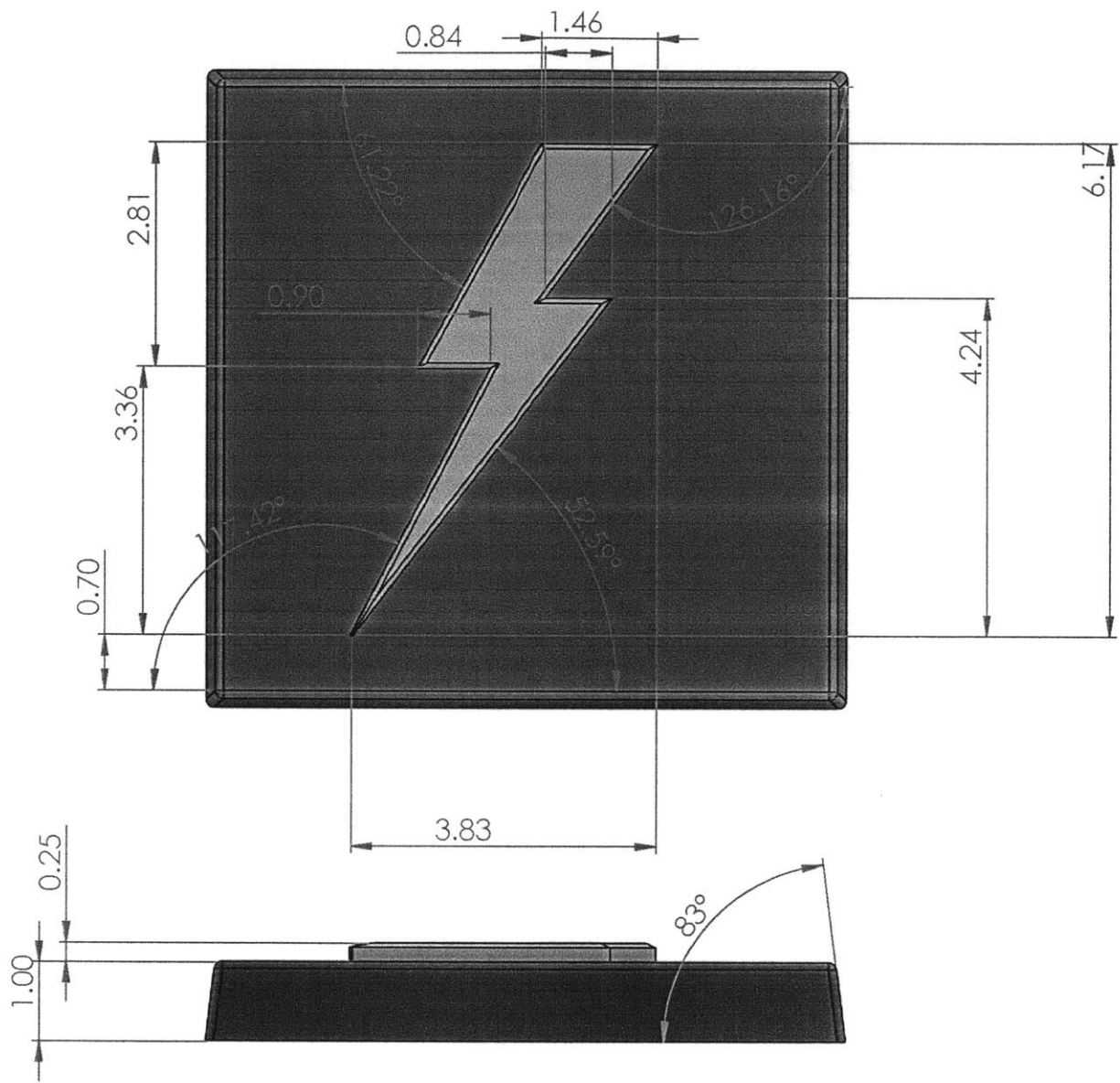
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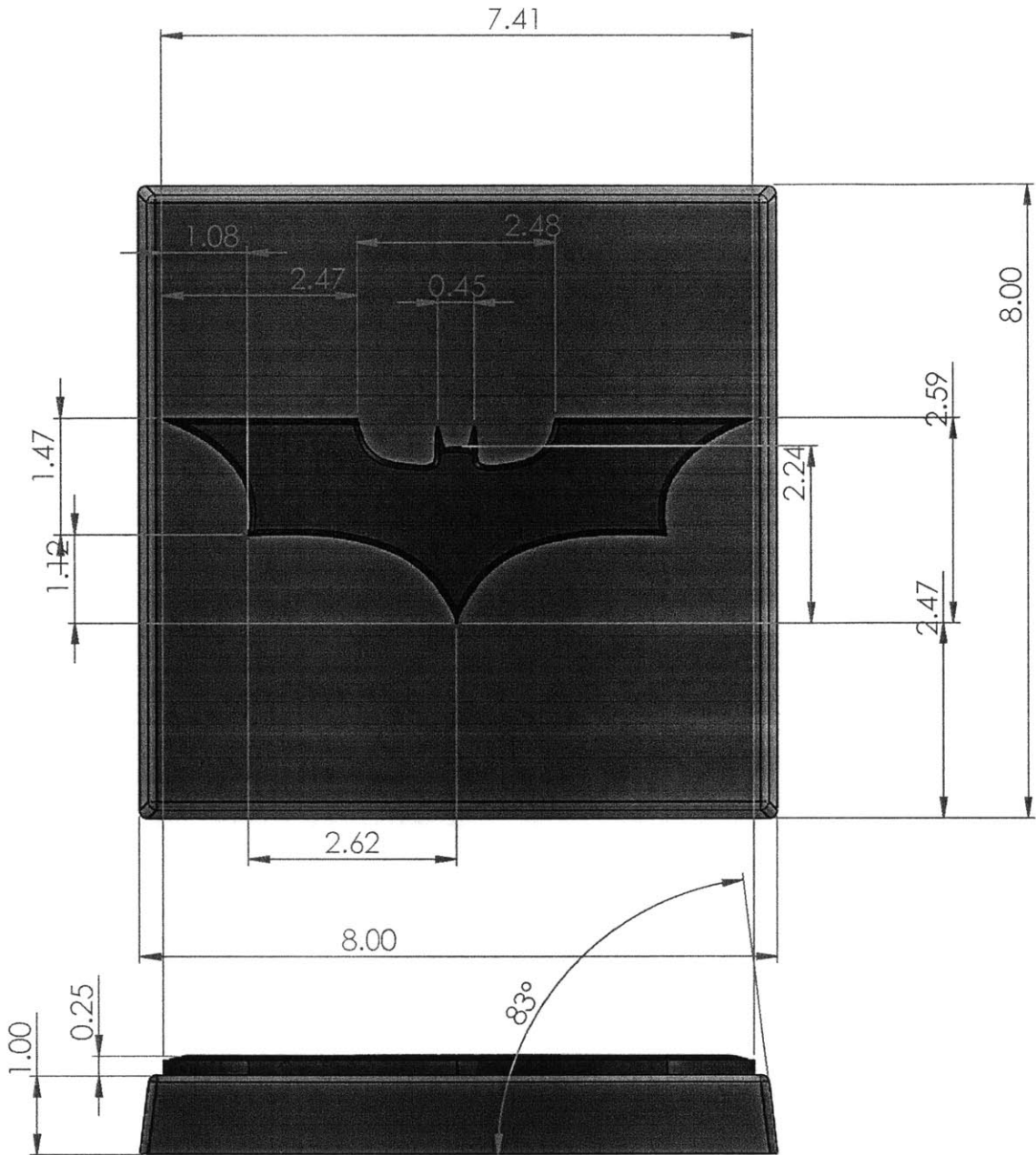
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SHEET 12 OF 43



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TITLE:

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DWG. NO.

**Batman-Squ-1C**

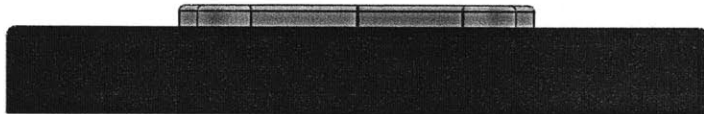
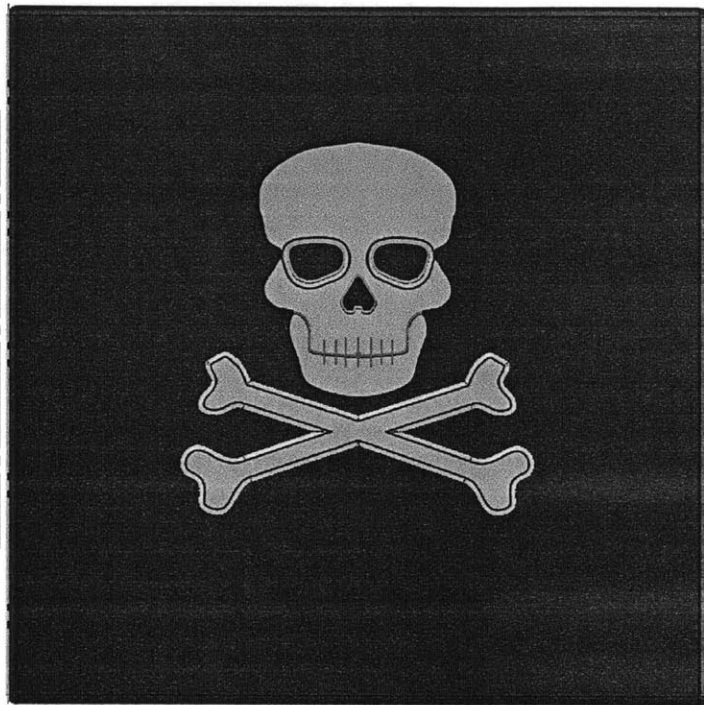
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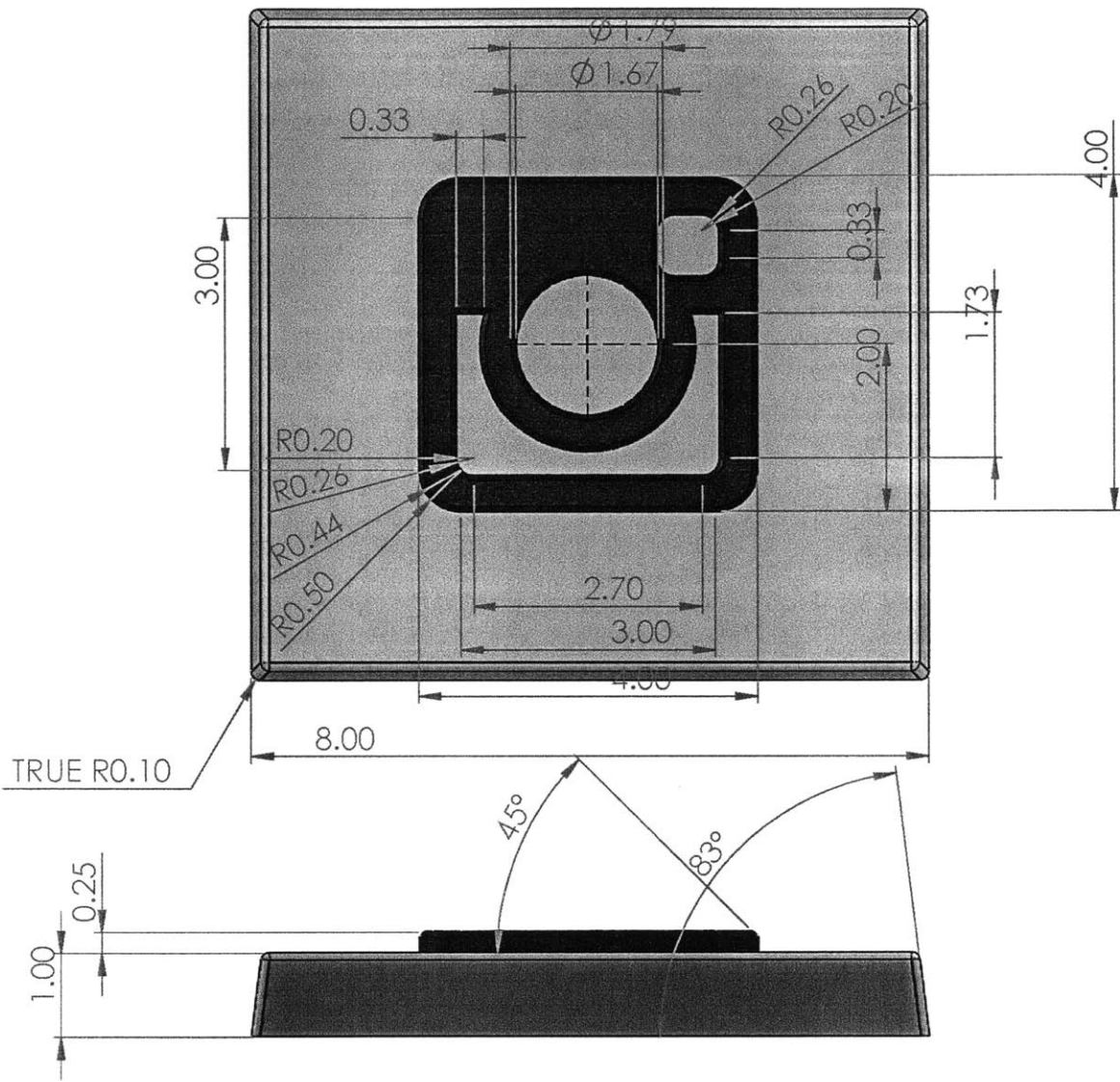
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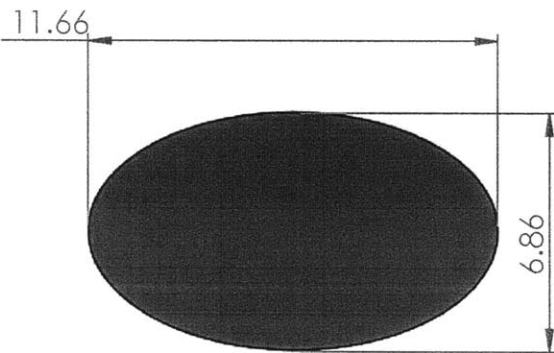
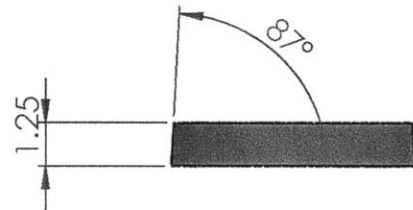
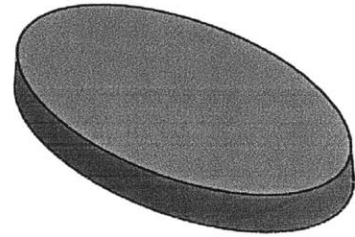
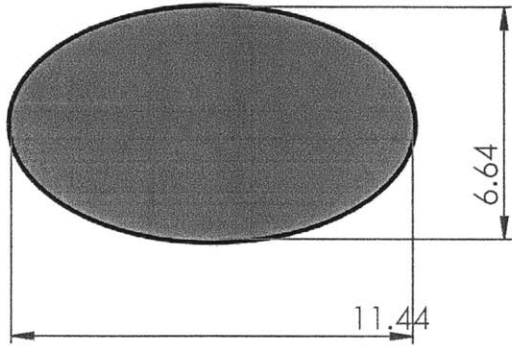
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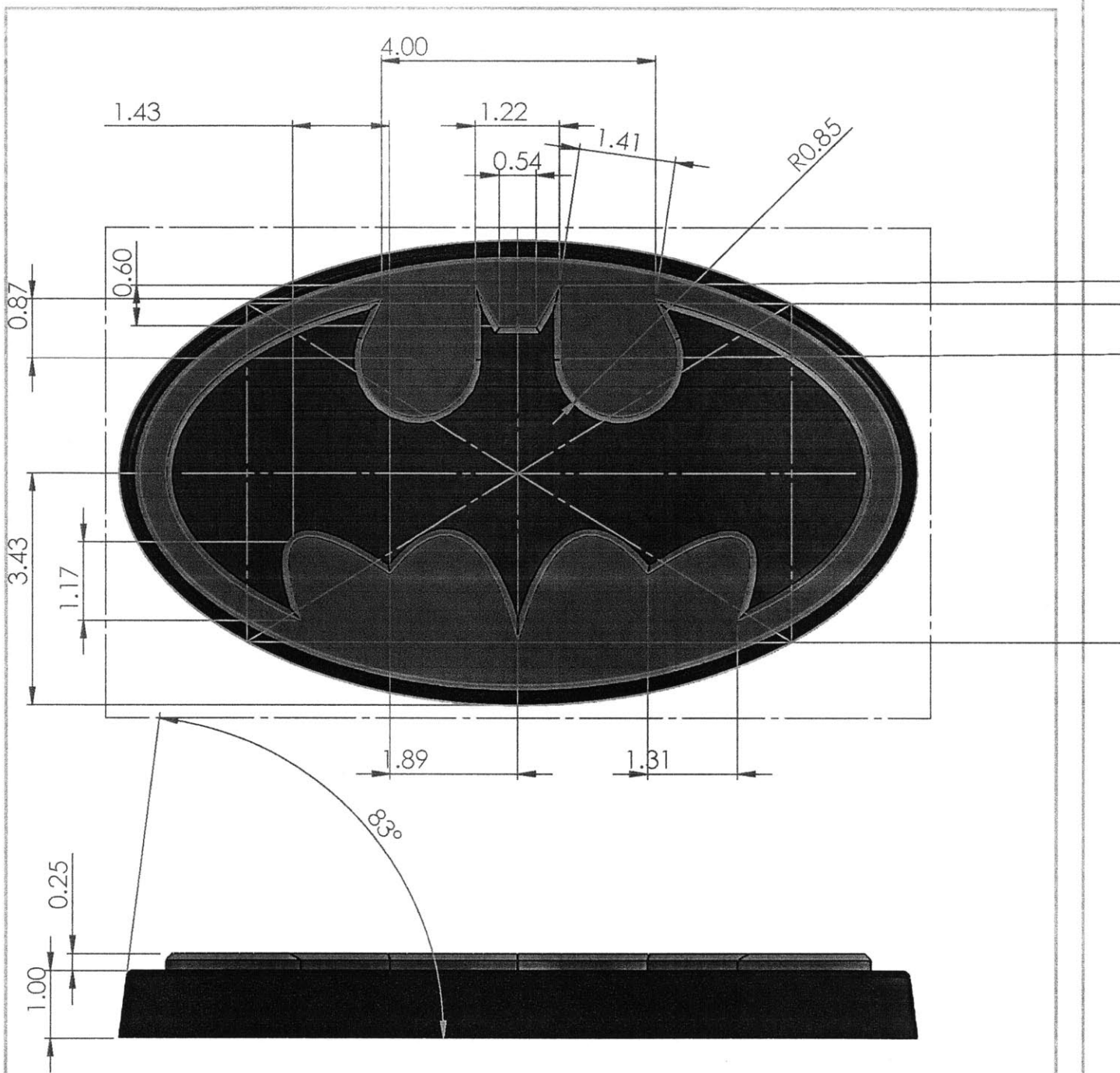
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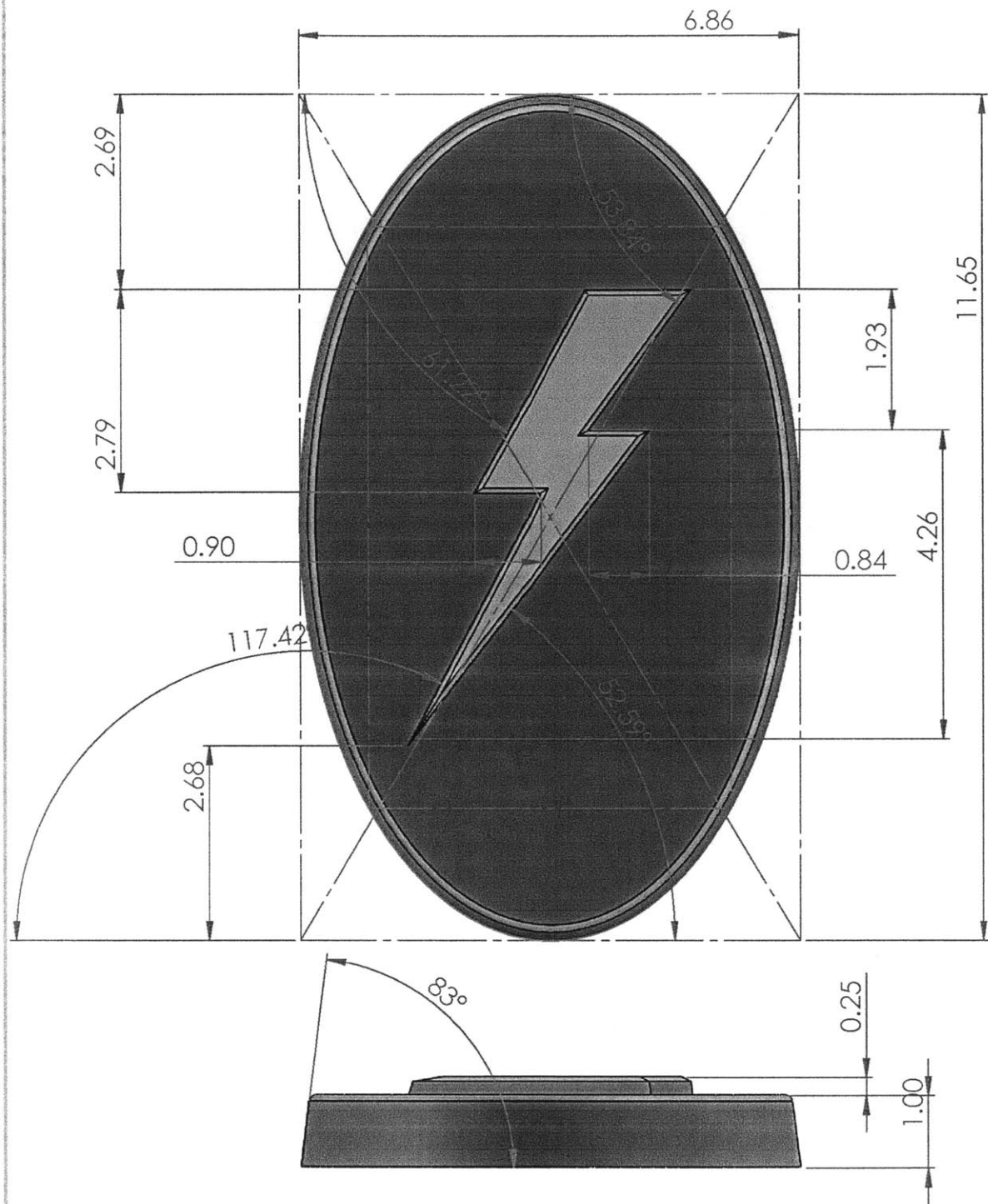
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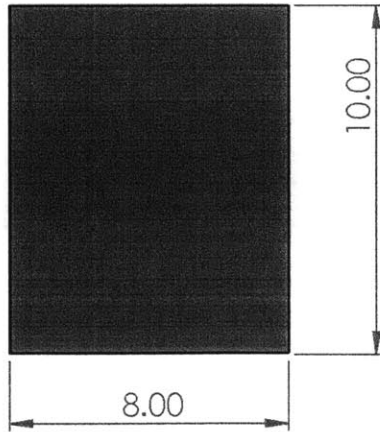
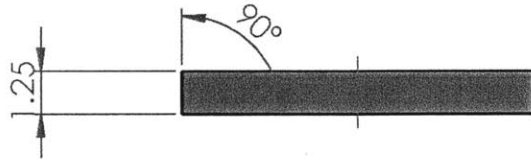
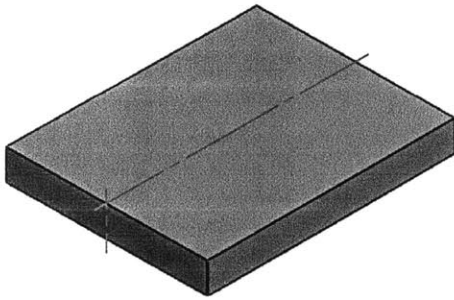
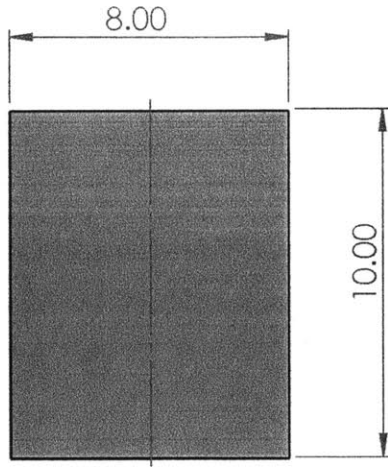


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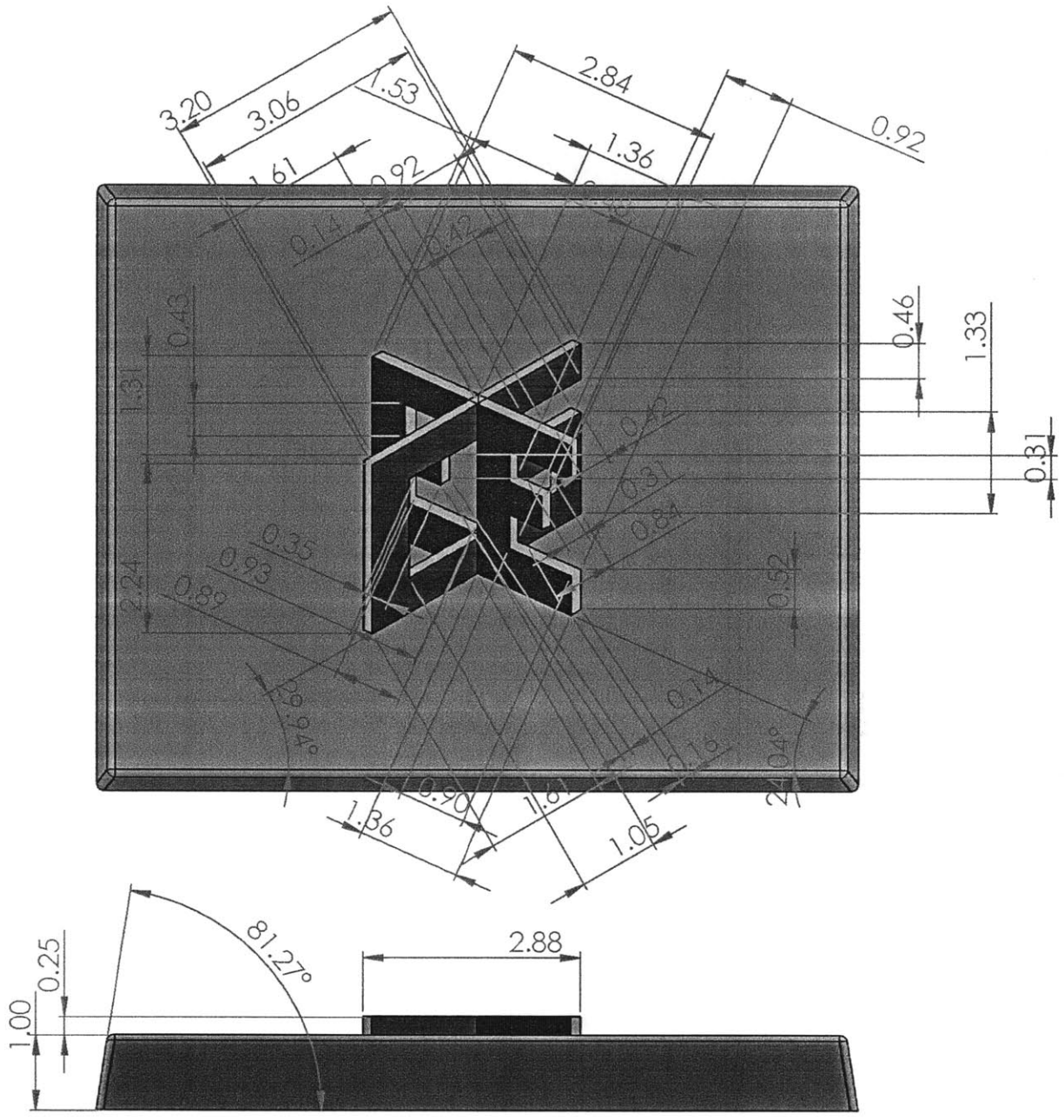
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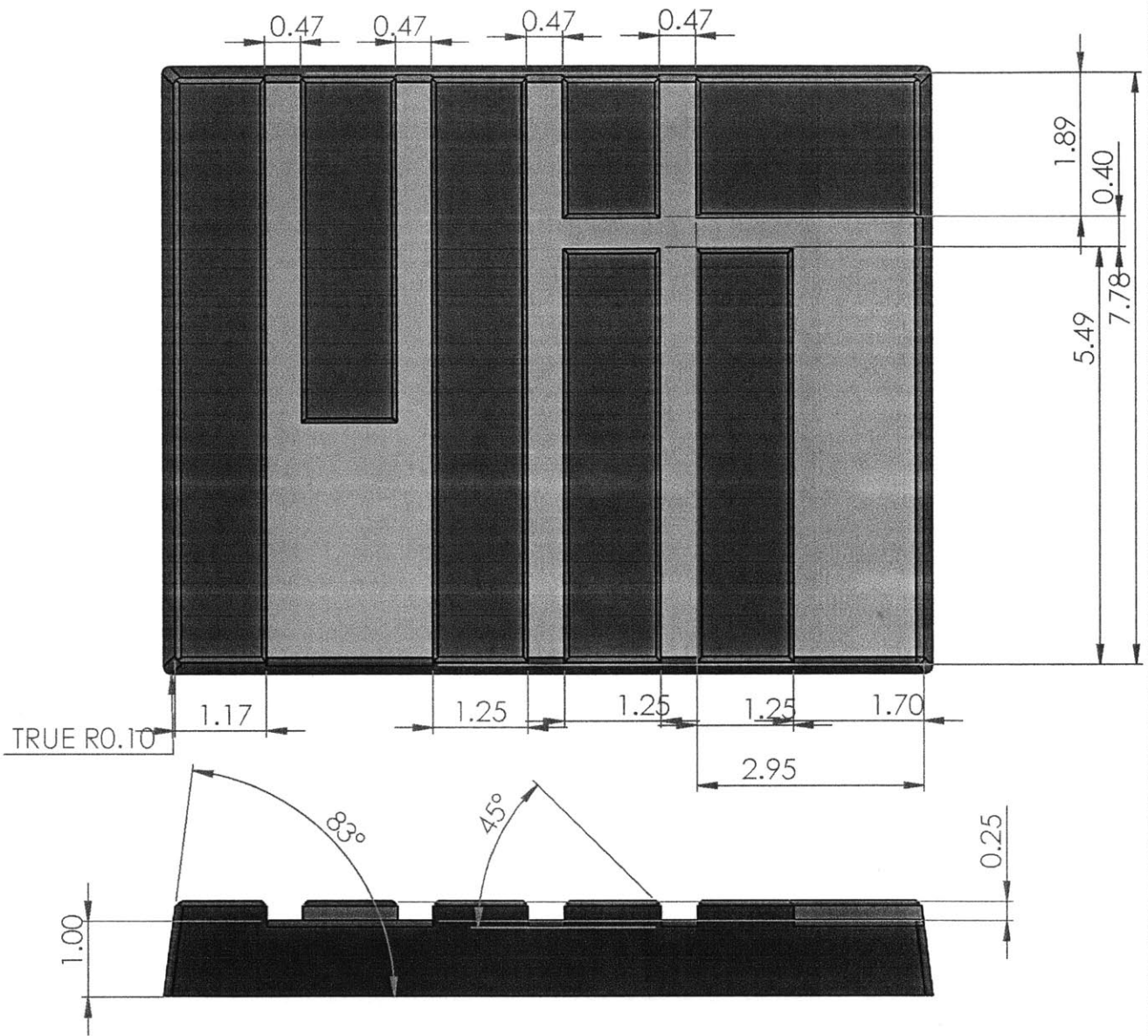


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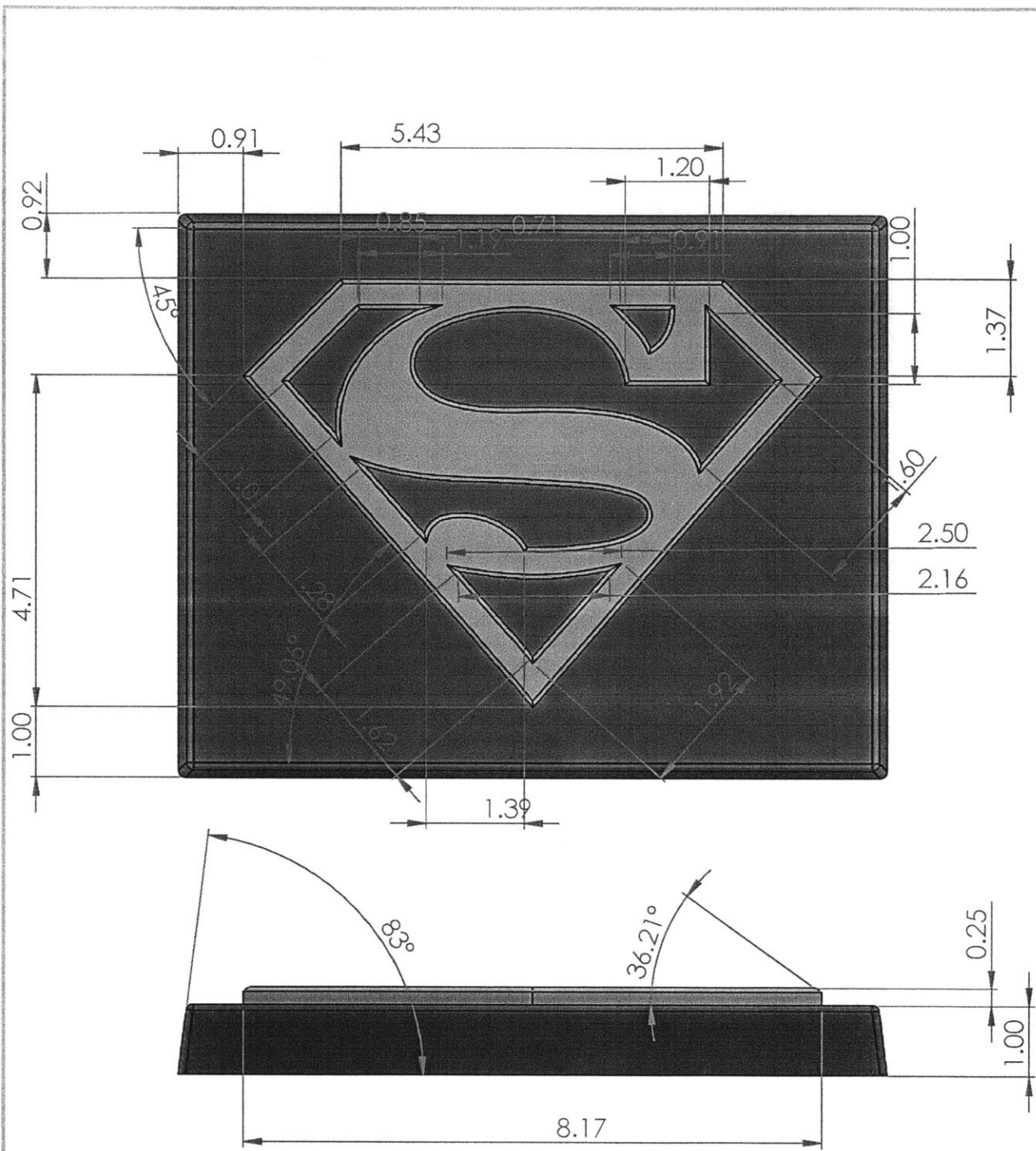
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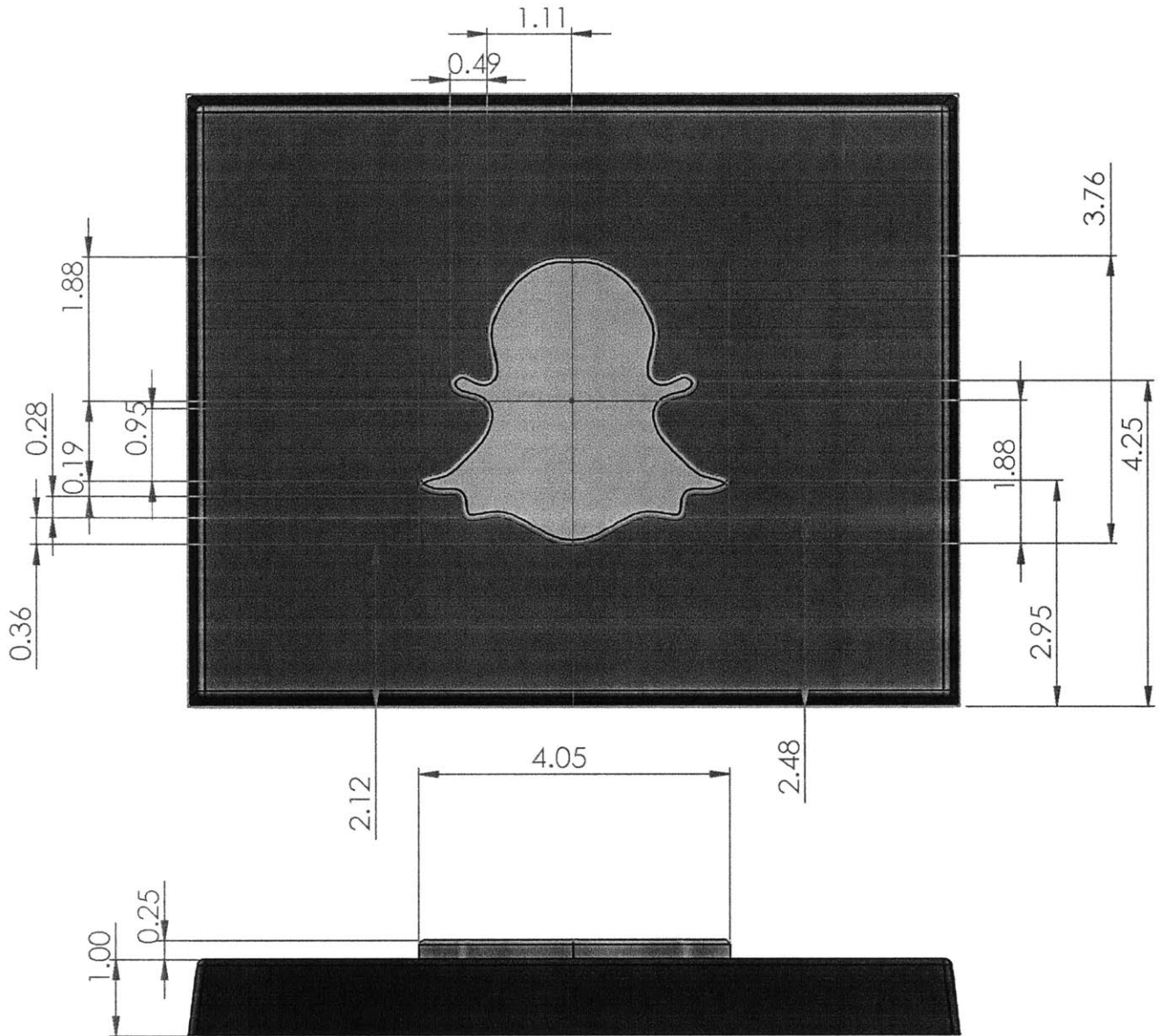
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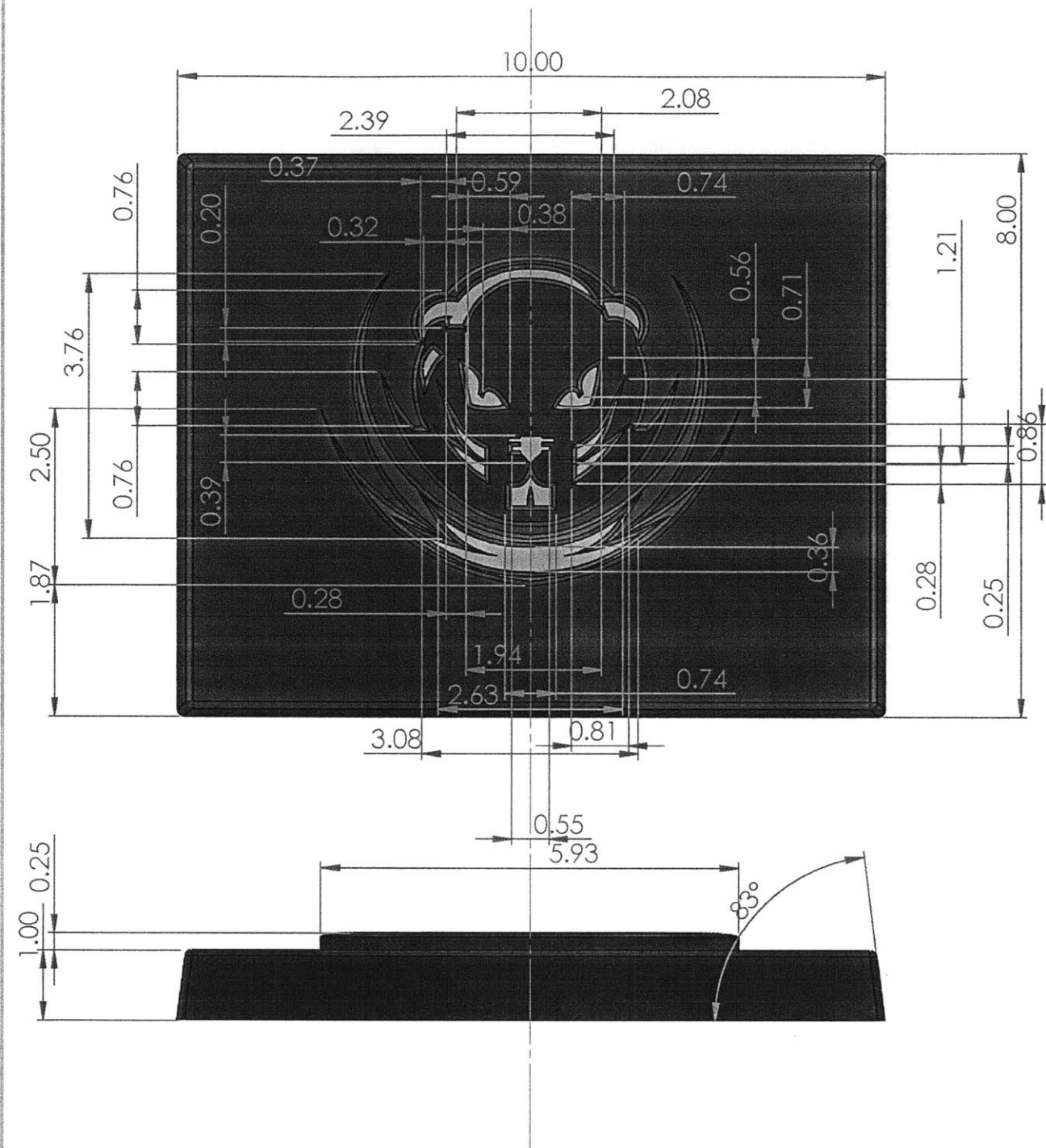
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Snapchat-2CP  
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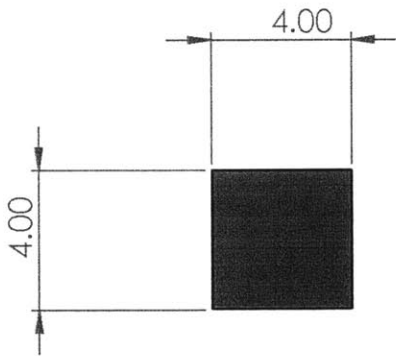
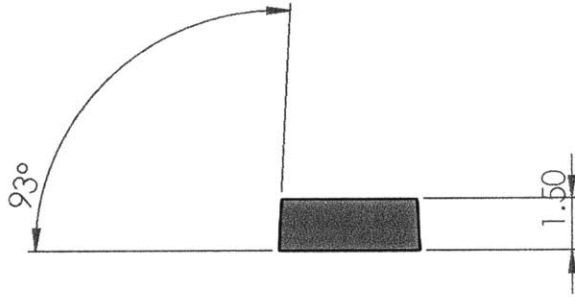
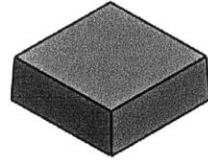
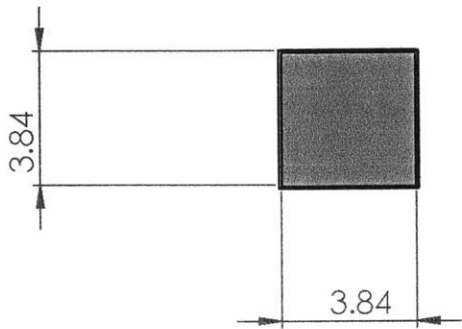
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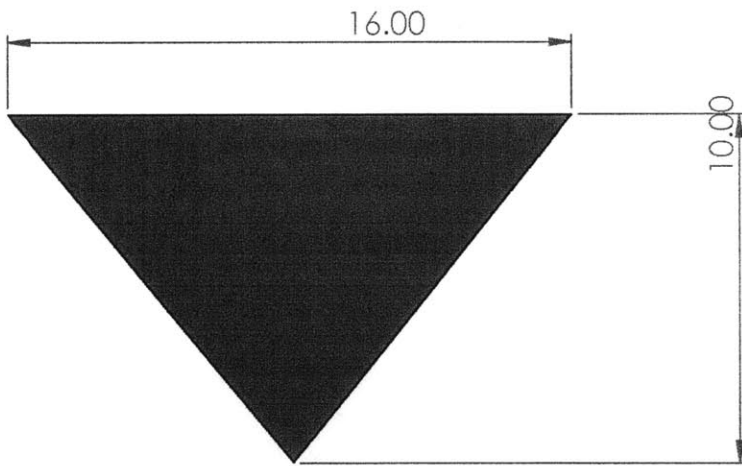
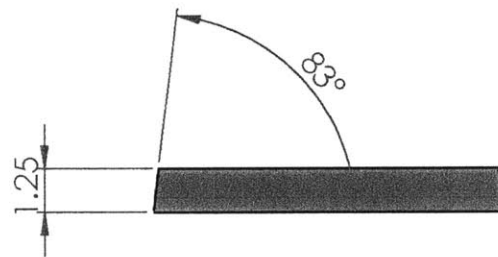
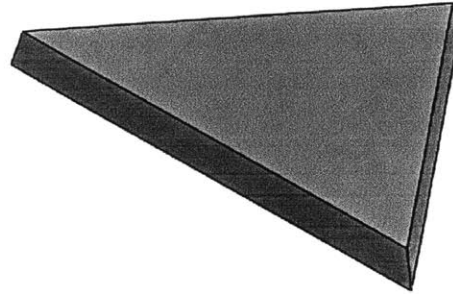
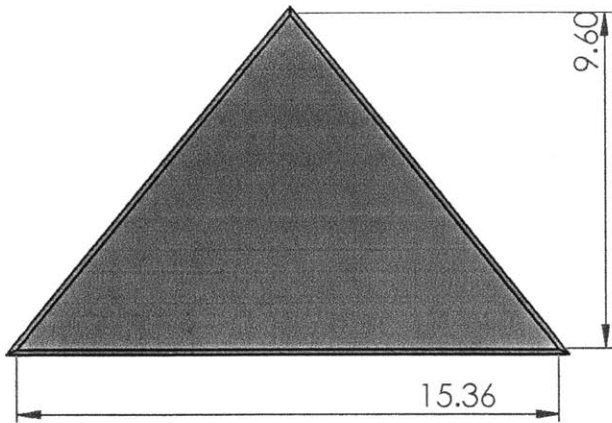




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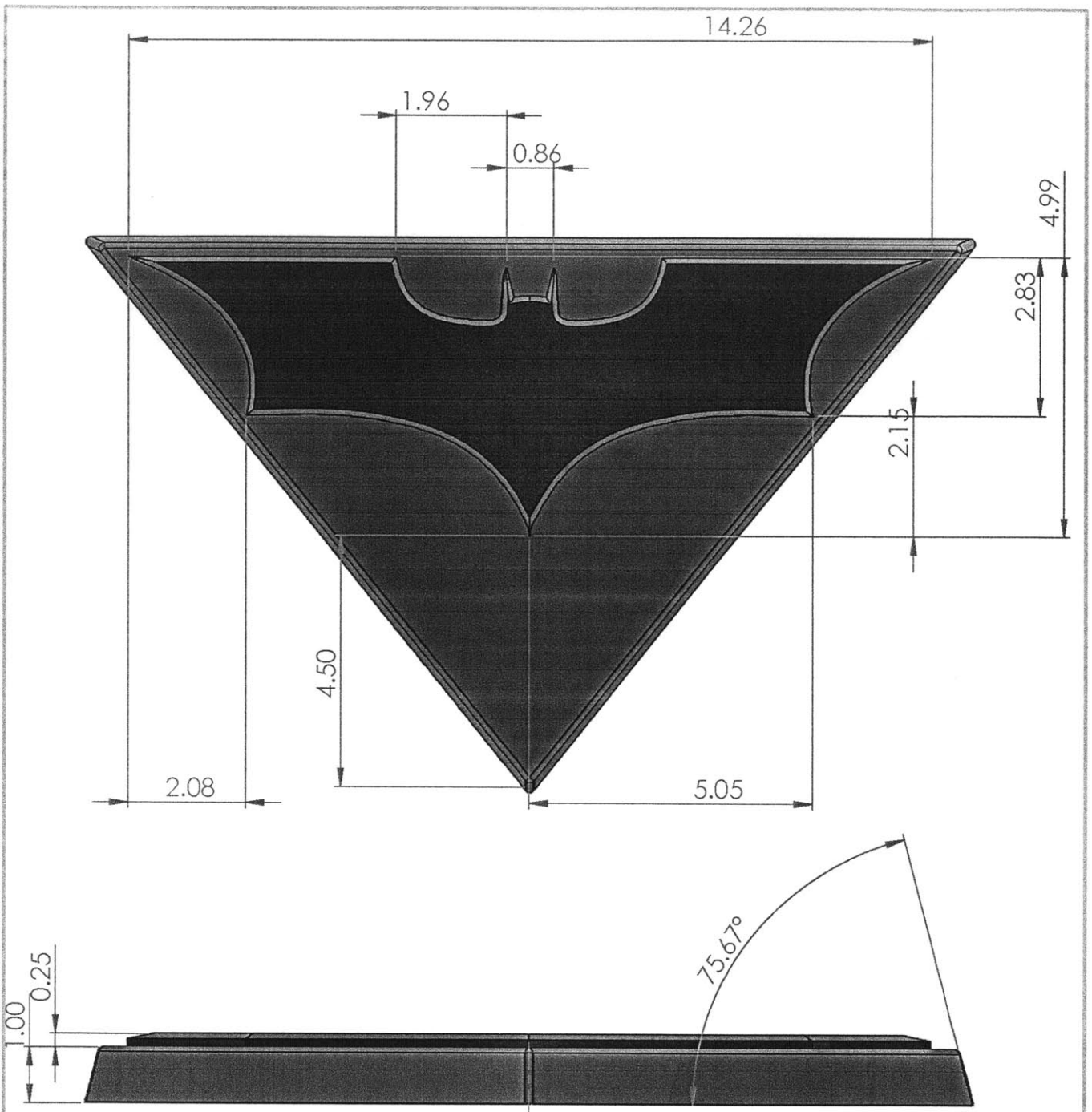
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WEIGHT:	
SHEET 30 OF 43	

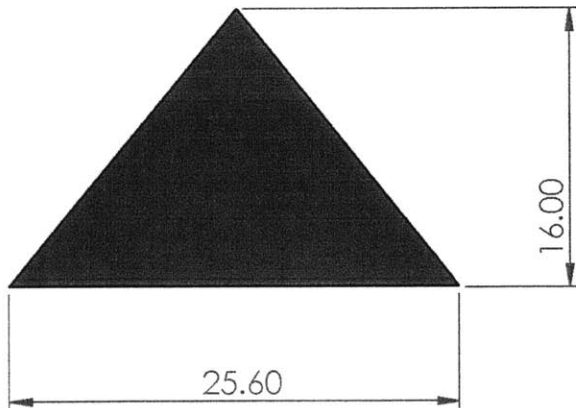
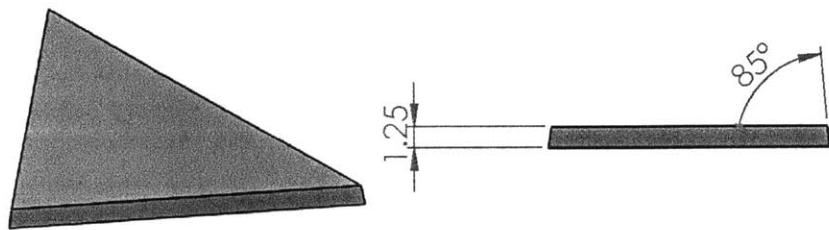
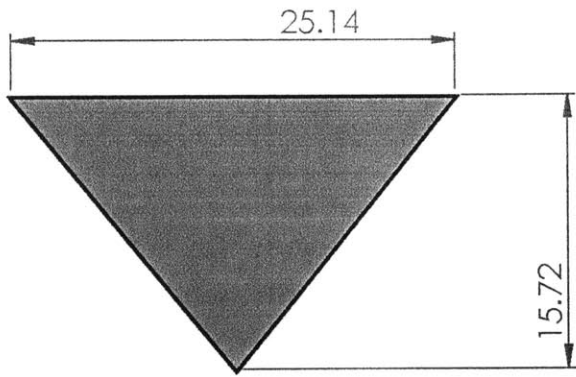
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55

A4



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:			FINISH:	DEBUR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION
DRAWN				TITLE:		
CHKD				DWG NO. <b>BatmanOld-TRI-1C</b> A4		
APPVD						
MFG						
Q.A						
<b>SolidWorks Student Edition.</b> <b>For Academic Use Only.</b>				56		
WEIGHT:				SCALE:1:5		SHEET 31 OF 43

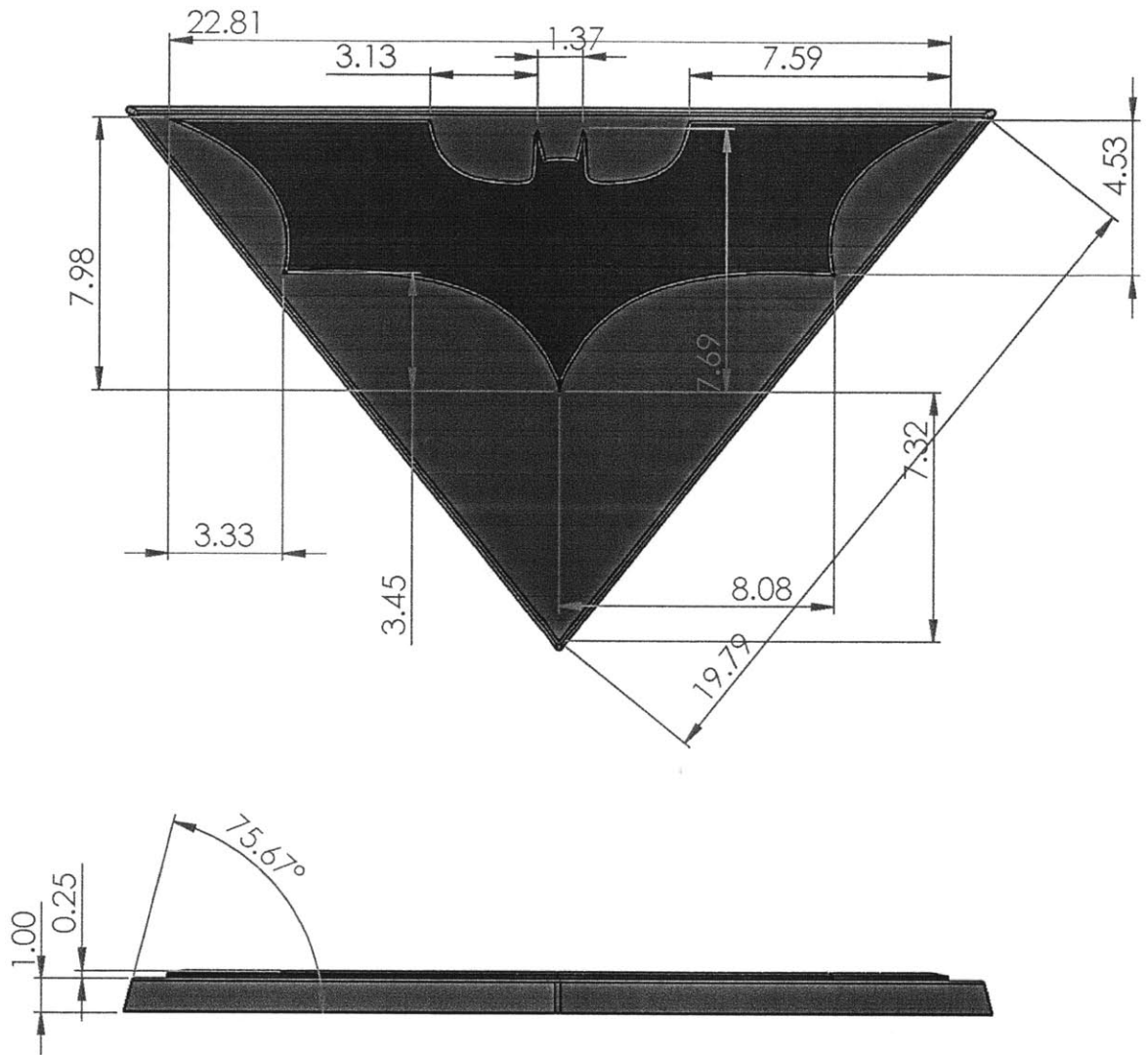


UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:			FINISH:	DEBUR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION
DRAWN					TITLE:	
CHK'D						
APPV'D						
MFG						
Q.A.					DWG NO. TRI-2C	
WEIGHT:					SCALE:1:5	
					SHEET 32 OF 43	

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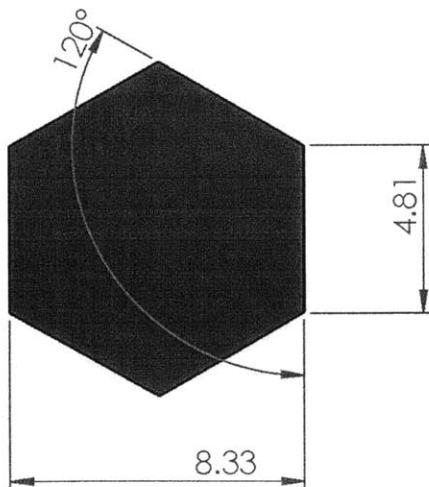
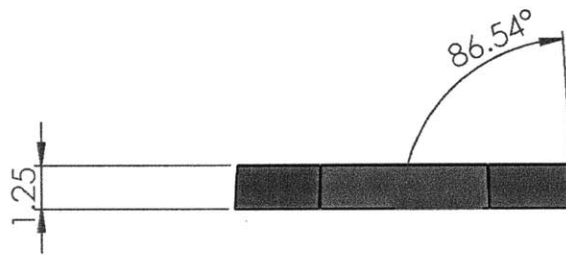
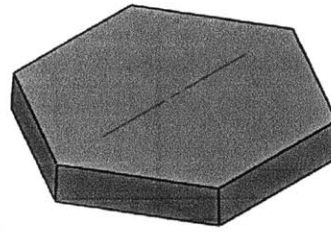
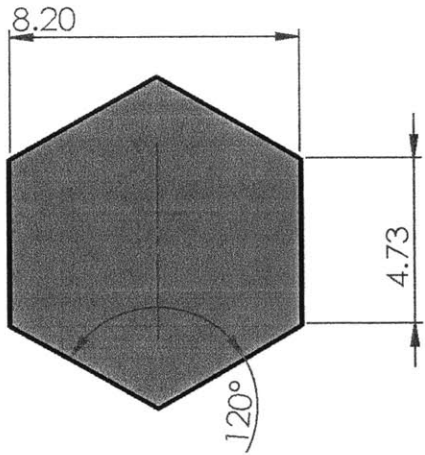
57

A4



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:			FINISH:		DEBUR AND BREAK SHARP EDGES		DO NOT SCALE DRAWING		REVISION	
DRAWN			SIGNATURE		DATE		TITLE:			
CHKD										
APPVD										
MFG										
Q.A							DWG NO		Batman-New-TRI-20 A4	
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DIMENSIONS ARE IN MILLIMETERS  
SURFACE FINISH:  
TOLERANCES:  
LINEAR:  
ANGULAR:

FINISH:

DEBUR AND  
BREAK SHARP  
EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHKD			
APPVD			
MFG			
Q.A			

TITLE:

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DWG NO.

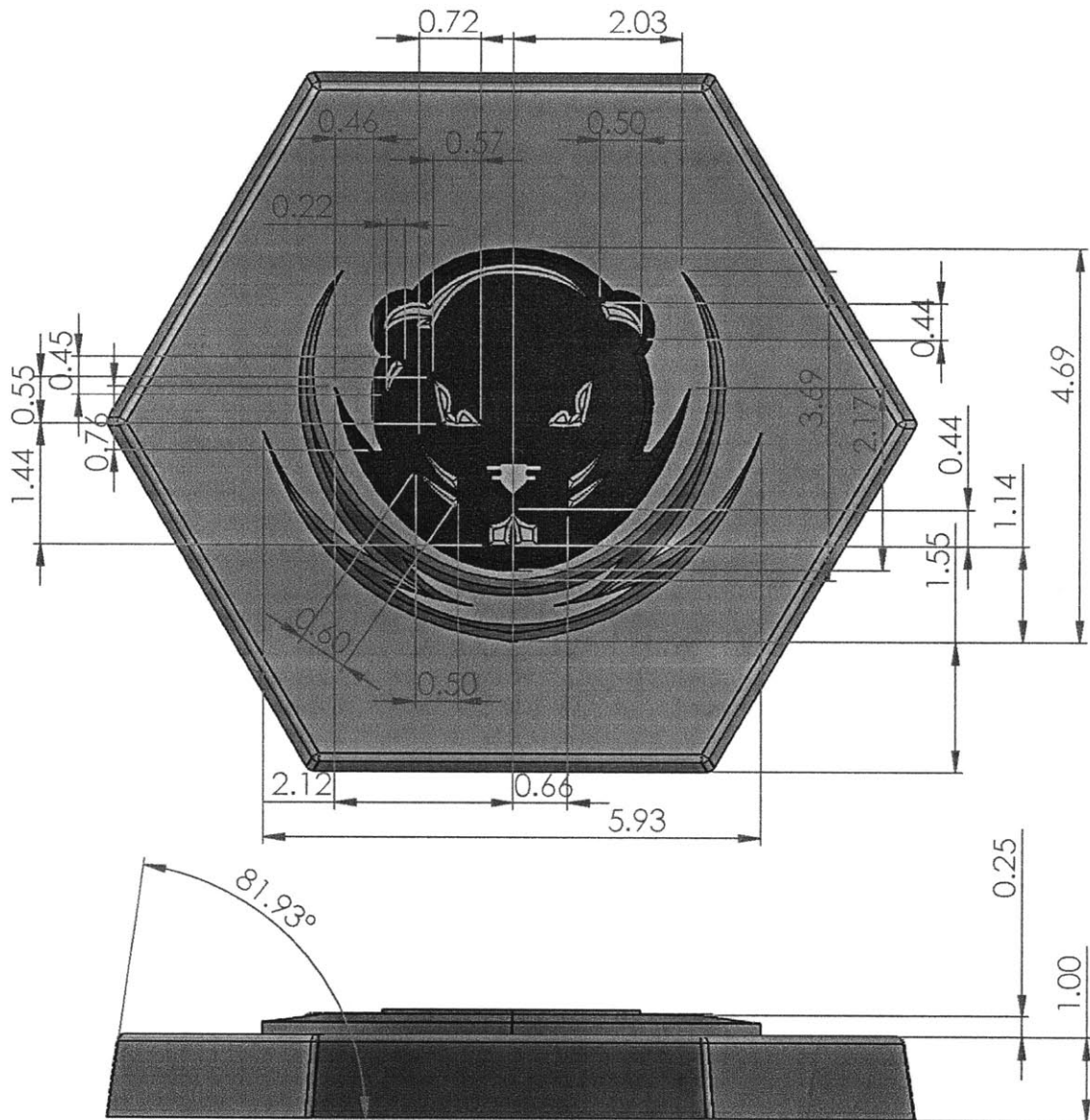
HEX-1C

A4

WEIGHT:

SCALE:1:5

SHEET 34 OF 43



UNLESS OTHERWISE SPECIFIED:  
 DIMENSIONS ARE IN MILLIMETERS  
 SURFACE FINISH:  
 TOLERANCES:  
 LINEAR:  
 ANGULAR:

FINISH:

DEBUR AND  
 BREAK SHARP  
 EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APP'VD			
MFG			
Q.A			

TITLE:

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DWG. NO.

**Beaver-Hex-1C**  
 60

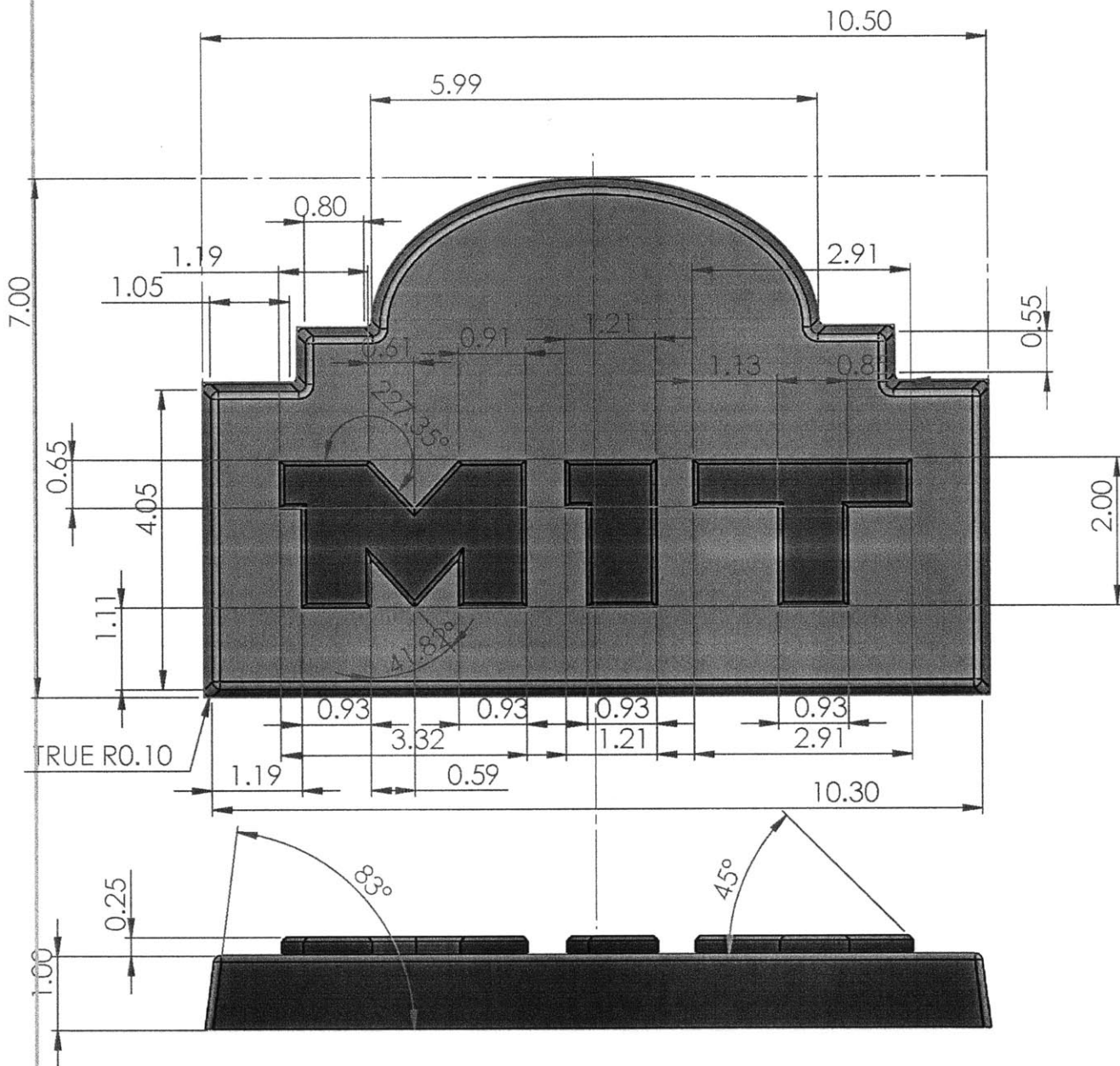
A4

WEIGHT:

SCALE:1:5

SHEET 35 OF 43





UNLESS OTHERWISE SPECIFIED:  
 DIMENSIONS ARE IN MILLIMETERS  
 SURFACE FINISH:  
 TOLERANCES:  
 LINEAR:  
 ANGULAR:

FINISH:

DEBUR AND  
 BREAK SHARP  
 EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHKD			
APPVD			
MFG			
Q.A			

TITLE:

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DWG NO.

**Dome-1C**

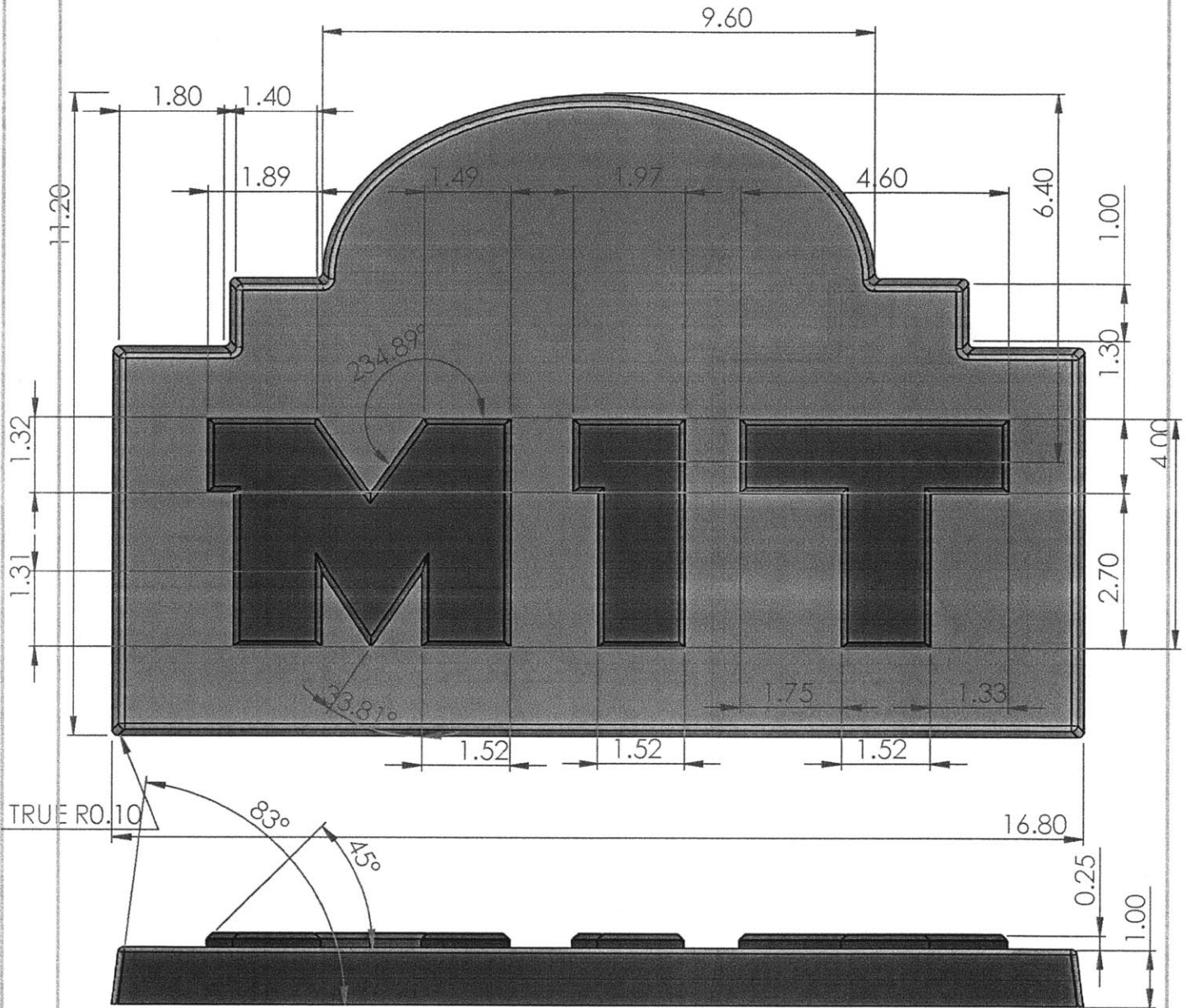
A4

61

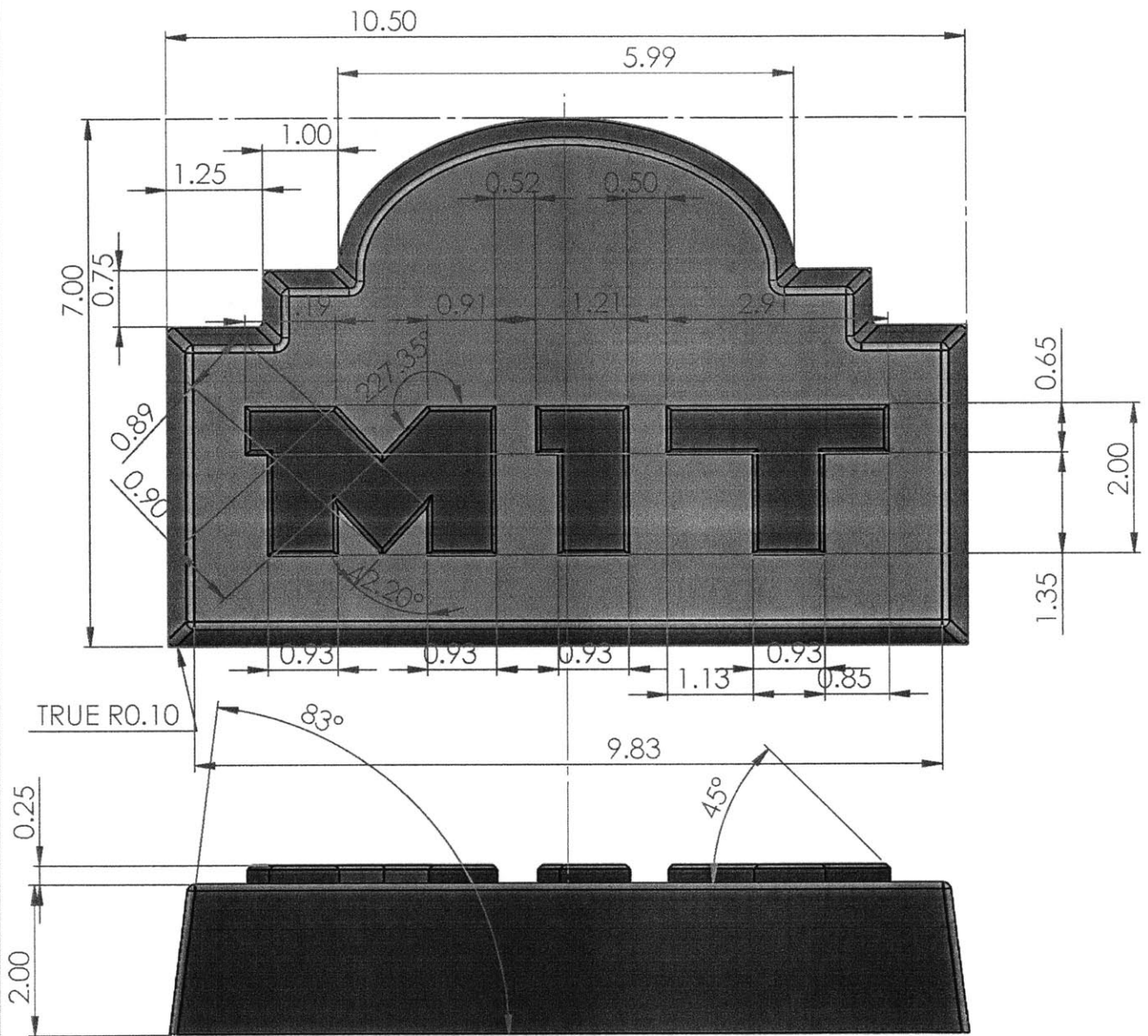
WEIGHT:

SCALE:1:5

SHEET 36 OF 43

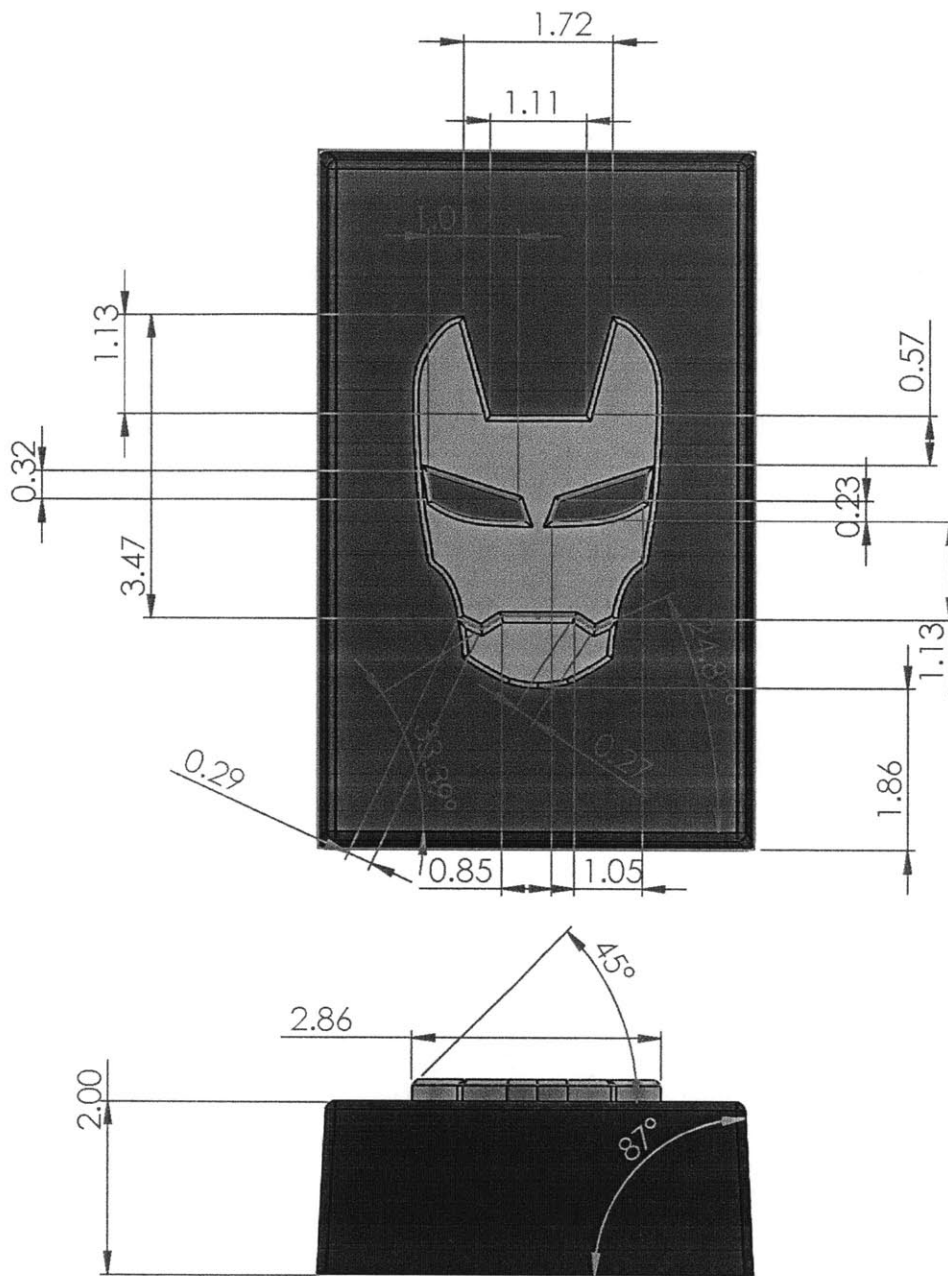


UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:			FINISH:	DEBUR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION
DRAWN				TITLE:		
CHK'D				<b>Dome-2CP</b> DWG NO. <span style="float: right;">A4</span> 62 SCALE: 1:5 <span style="float: right;">SHEET 37 OF 43</span>		
APPVD						
MFG						
Q.A						
<b>SolidWorks Student Edition.</b> <b>For Academic Use Only.</b>				WEIGHT:		

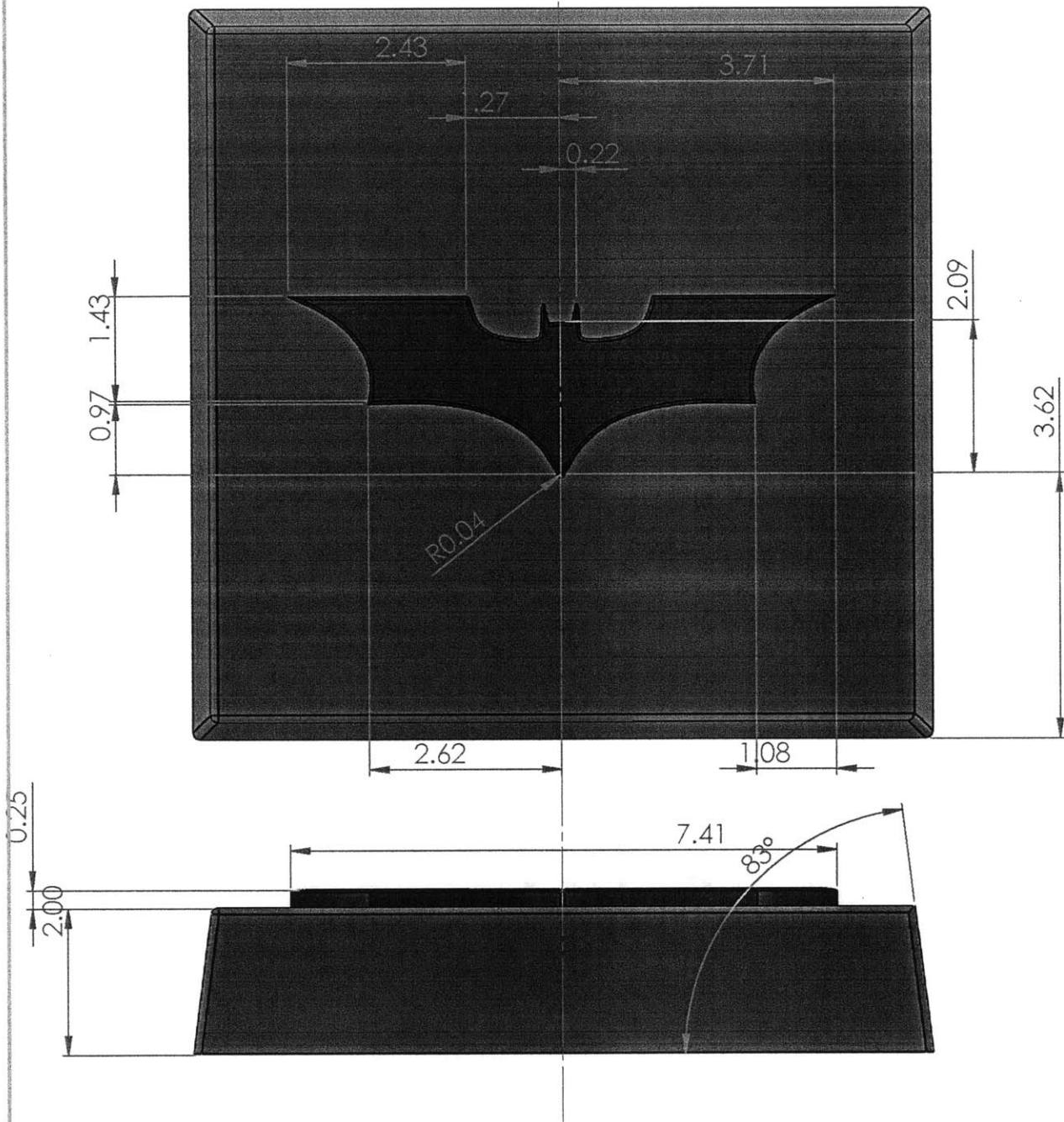


UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:			FINISH:	DEBUR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION
DRAWN				TITLE:		
CHKD				DWG NO. <b>Dome-2CS</b> <span style="float: right;">A4</span> 63 SHEET 38 OF 43		
APPVD						
MFG						
G.A						
WEIGHT:						
SCALE: 1:5						

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DRAWN				TITLE:		
CHK'D				DWG NO. <b>Ironman-Rec-2CS</b> A4 64 SCALE:1:5 SHEET 39 OF 43		
APP'VD						
MFG						
Q.A						
<b>SolidWorks Student Edition.</b> <b>For Academic Use Only.</b>						
WEIGHT:						



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 DIMENSIONS ARE IN MILLIMETERS  
 SURFACE FINISH:  
 TOLERANCES:  
 LINEAR:  
 ANGULAR:

FINISH:

DEBUR AND  
 BREAK SHARP  
 EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHKD			
APPVD			
MFG			
Q.A			

TITLE:

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DWG NO.

**Batman-Rec-2CS**

A4

65

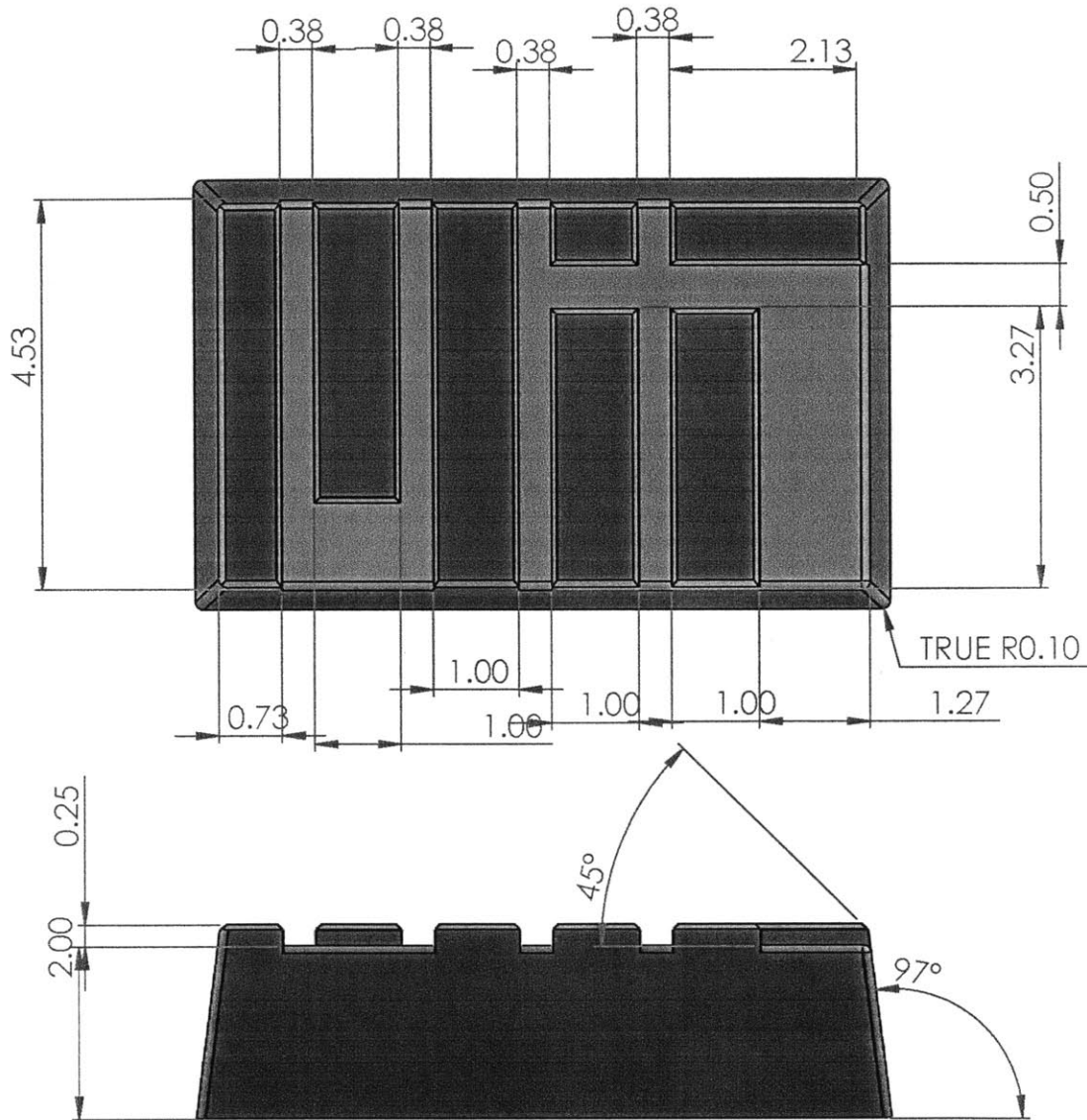
WEIGHT:

SCALE:1:5

SHEET 40 OF 43

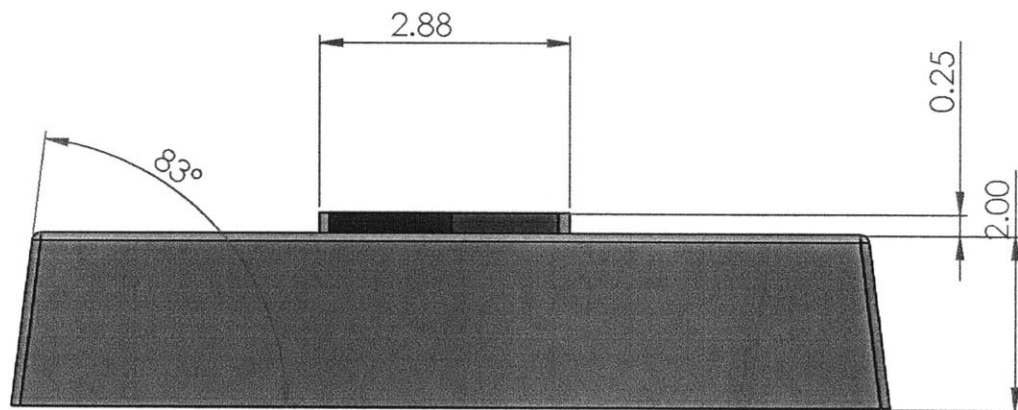
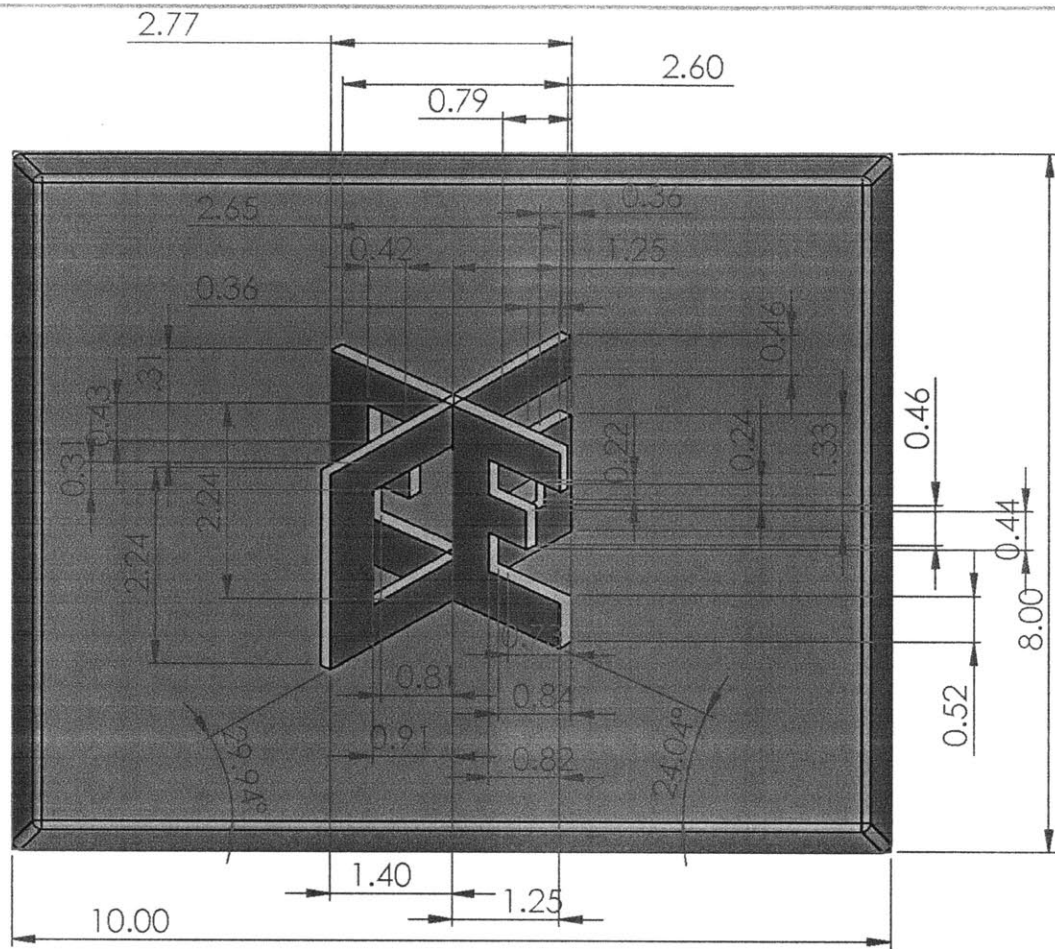






UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:			FINISH:	DEBUR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION
DRAWN			NAME		TITLE:	
CHKD			SIGNATURE		DWG NO.	
APPVD			DATE		MIT-REC-2CS	
MFG			DATE		A4	
G.A.			DATE		67	
WEIGHT:			SCALE: 1:5		SHEET 42 OF 43	

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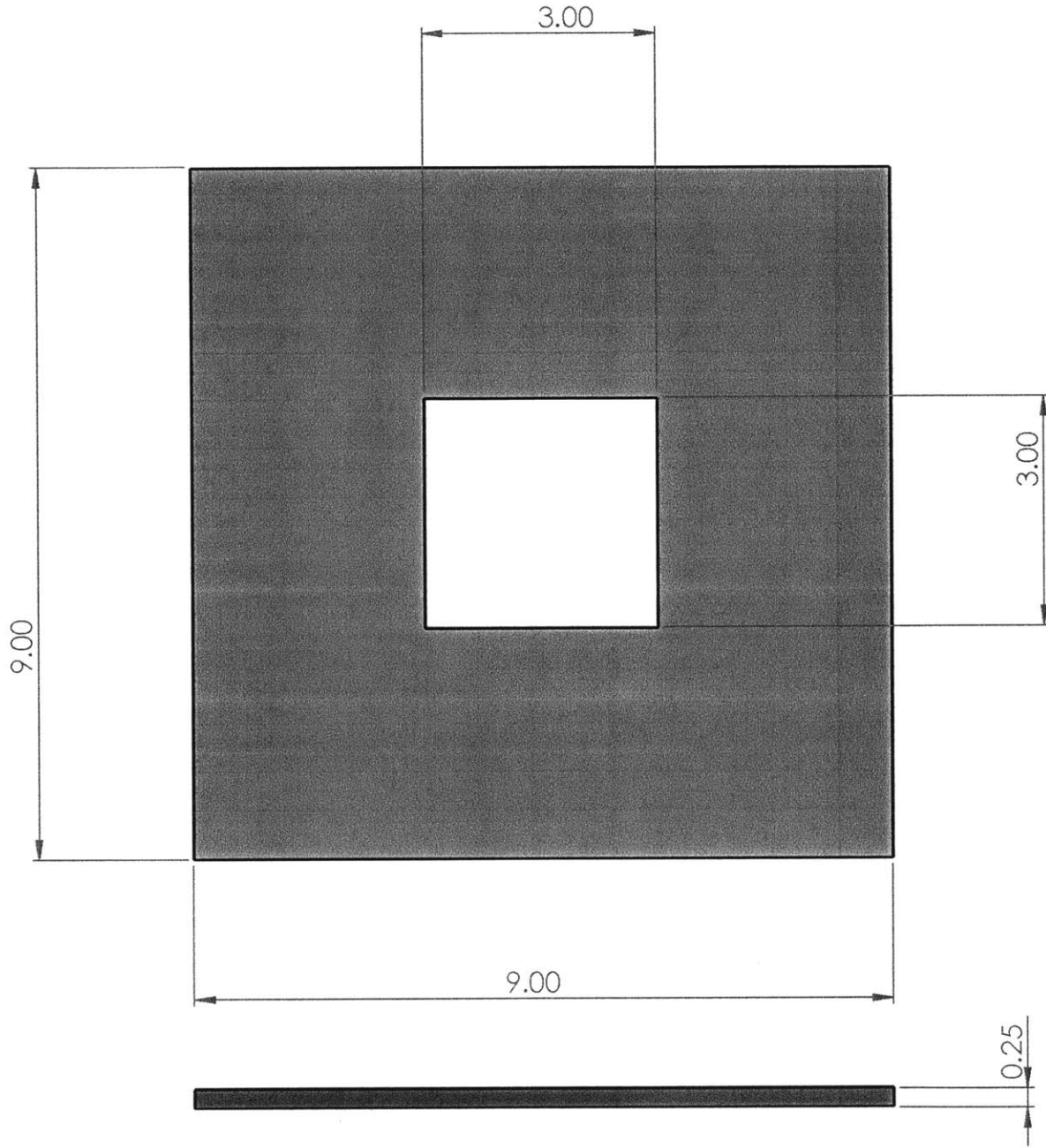
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DRAWN					TITLE:	
CHK'D						
APPV'D						
MFG						
QA						
<b>SolidWorks Student Edition.</b> <b>For Academic Use Only.</b>					DWG NO.	A4
WEIGHT:					SCALE:1:5	SHEET 43 OF 43

EECS-4CSP

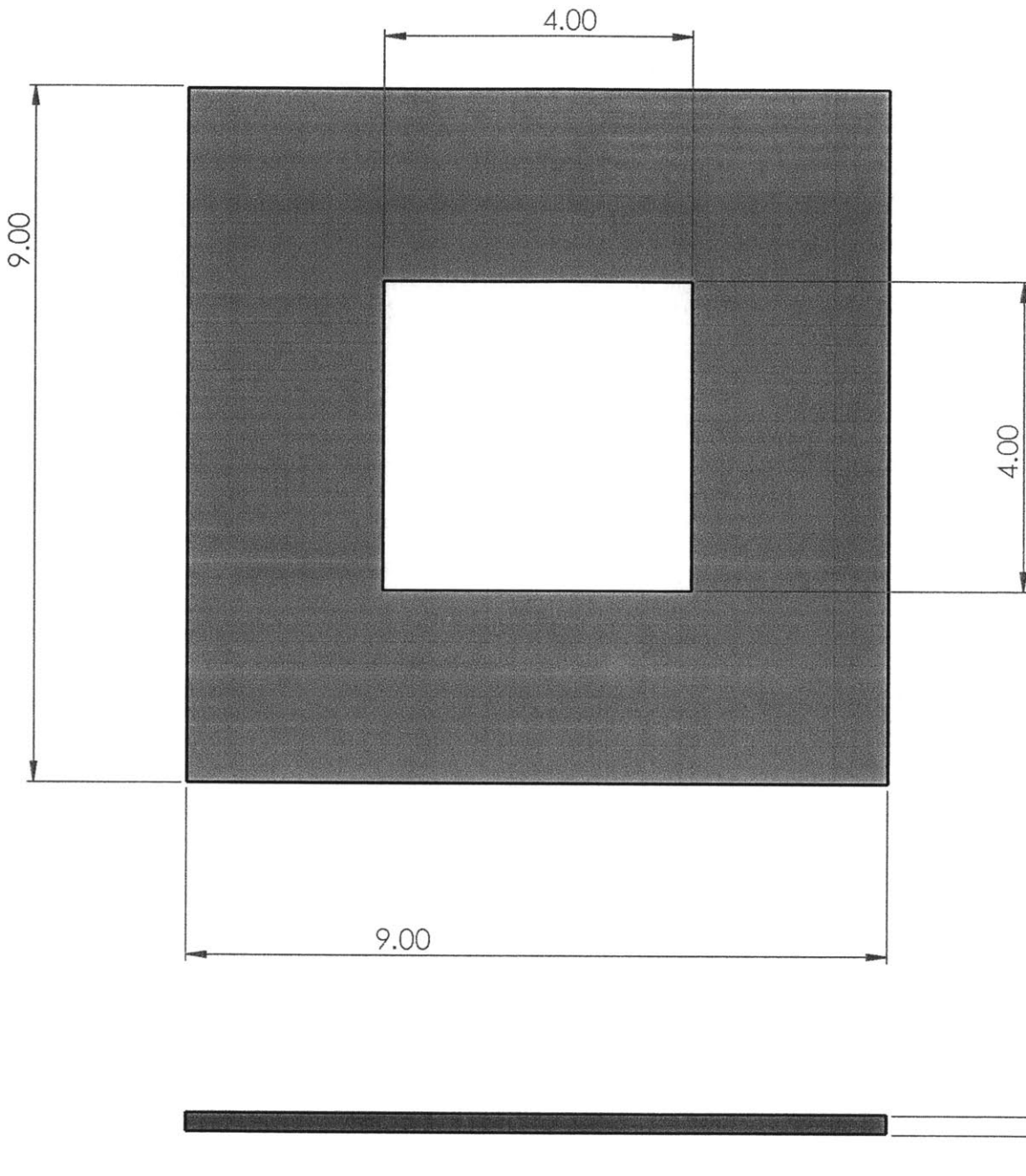
68



# Appendix B: Base Drawings



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:				FINISH:	DEBUR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION
DRAWN				TITLE:			
CHKD				<b>SolidWorks Student Edition.</b> <b>For Academic Use Only.</b>			
APPVD							
MFG							
Q.A							
WEIGHT:				DWG NO. <b>9by9-4square</b>		A4	
				SCALE:1:5		SHEET 1 OF 1	

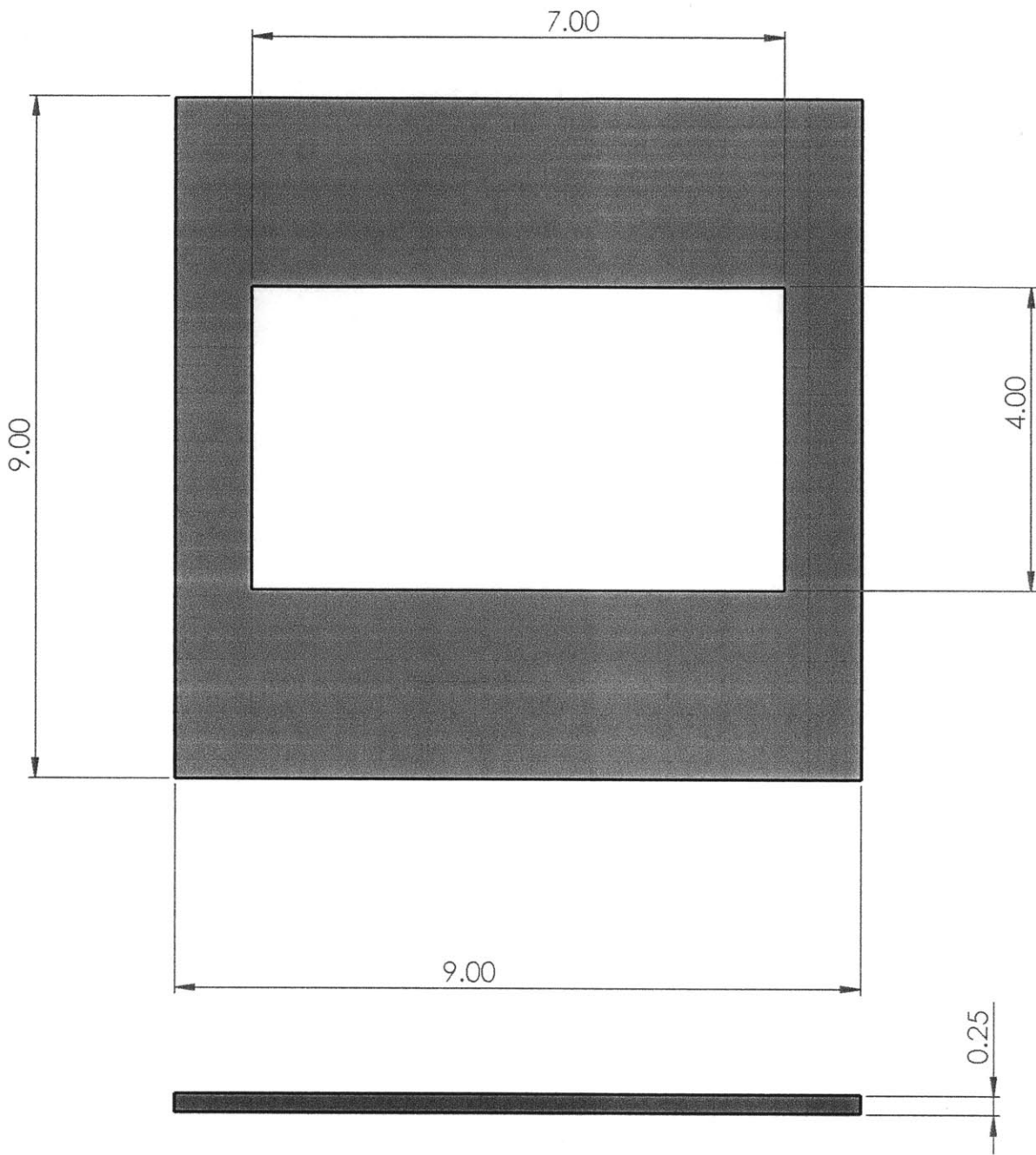


UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:		FINISH:		DEBUR AND BREAK SHARP EDGES		DO NOT SCALE DRAWING		REVISION	
DRAWN		SIGNATURE		DATE		TITLE:			
CHK'D									
APP'VD									
MFG									
Q.A						DWG NO. <b>9by9-5square</b>		A4	
						SCALE: 1:5		SHEET 1 OF 1	
				WEIGHT:					

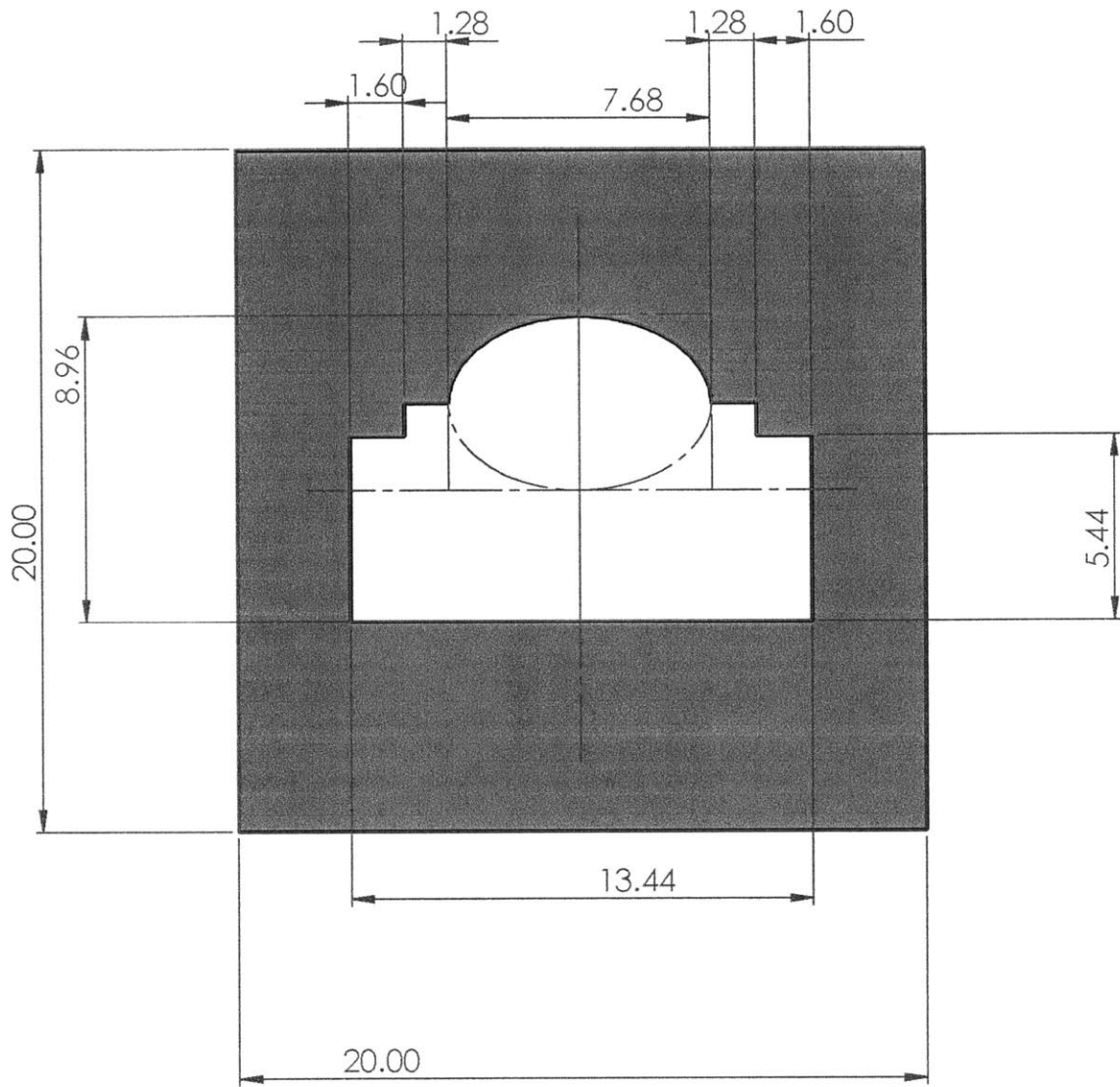
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**9by9-5square**  
70

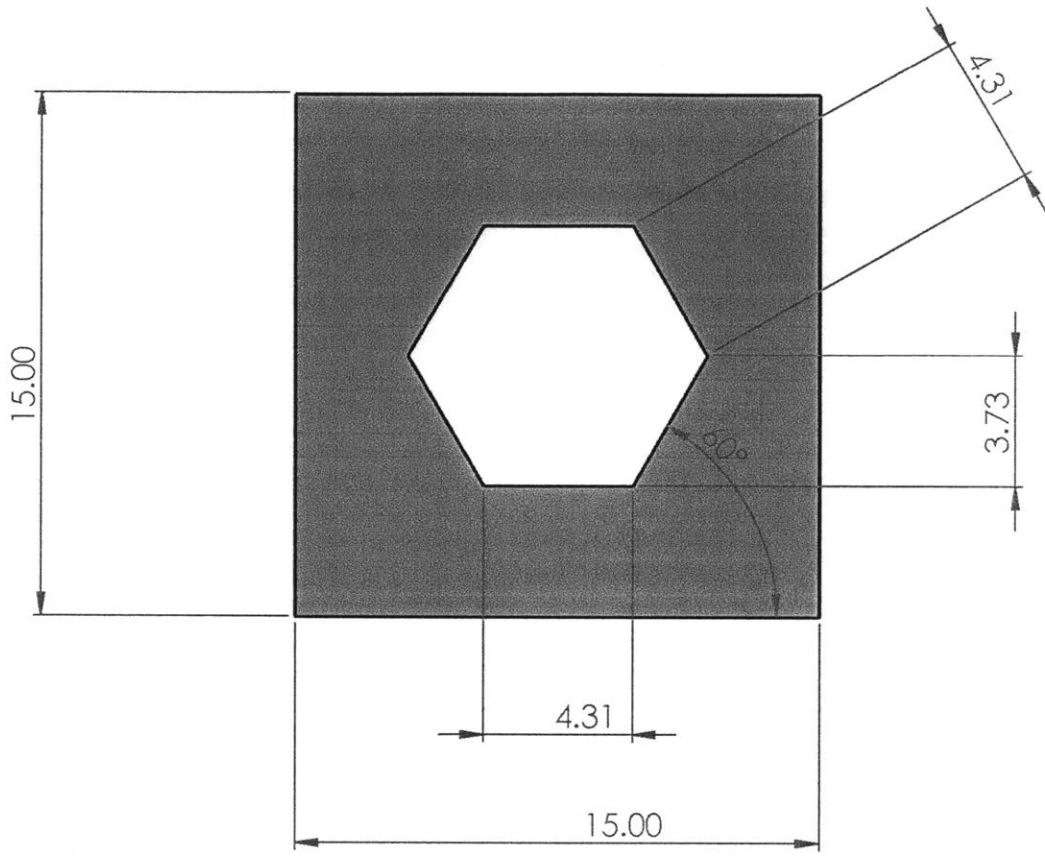




UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:		FINISH:	DEBUR AND BREAK SHARP EDGES		DO NOT SCALE DRAWING	REVISION
DRAWN		NAME	SIGNATURE	DATE	TITLE:	
CHK'D					<b>SolidWorks Student Edition.</b> <b>For Academic Use Only.</b>	
APP'VD						
MFG						
Q.A						
					DWG NO.	9by9-rec1c
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				WEIGHT:		72
						SHEET 1 OF 1



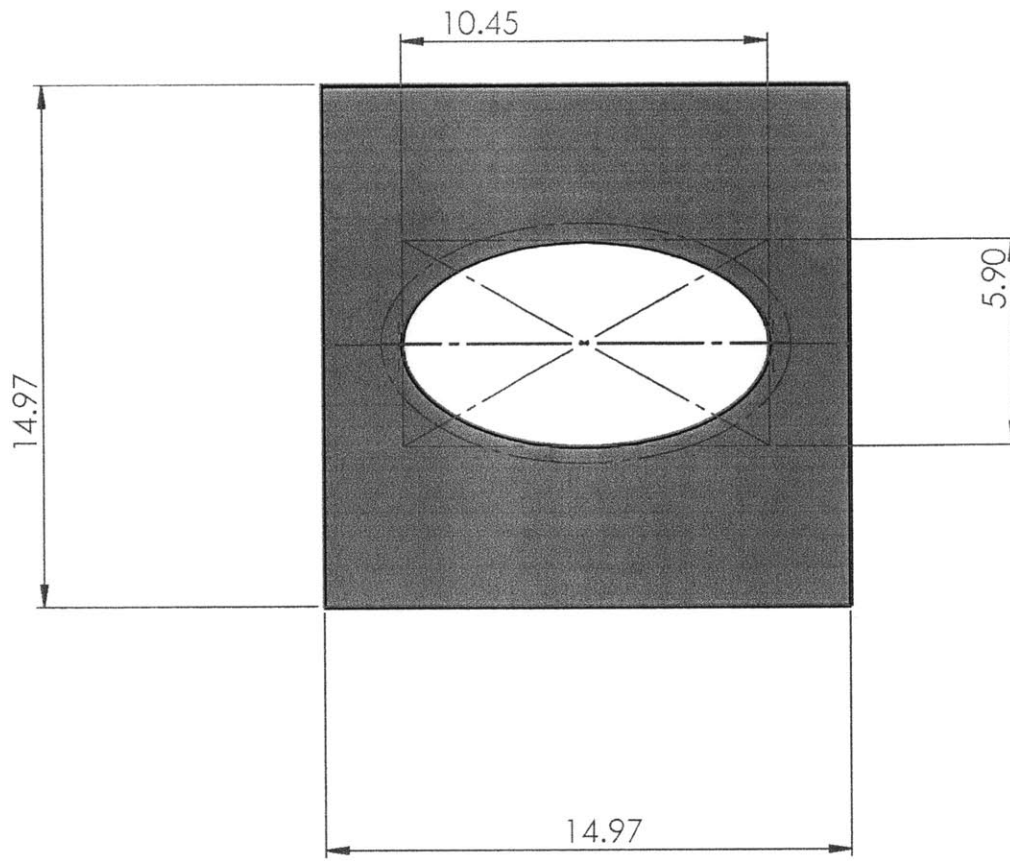
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DRAWN				SIGNATURE		DATE		TITLE:				
CHKD												
APPVD												
MFG												
Q.A												
<b>SolidWorks Student Edition.</b> <b>For Academic Use Only.</b>								DWG NO.		15by15-dome1c		A4
										73		
				WEIGHT:				SCALE:1:10		SHEET 1 OF 1		



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:		FINISH:		DEBUR AND BREAK SHARP EDGES		DO NOT SCALE DRAWING		REVISION	
DRAWN		SIGNATURE		DATE		TITLE:			
CHKD									
APPV'D									
MFG									
Q.A						DWG NO.		A4	
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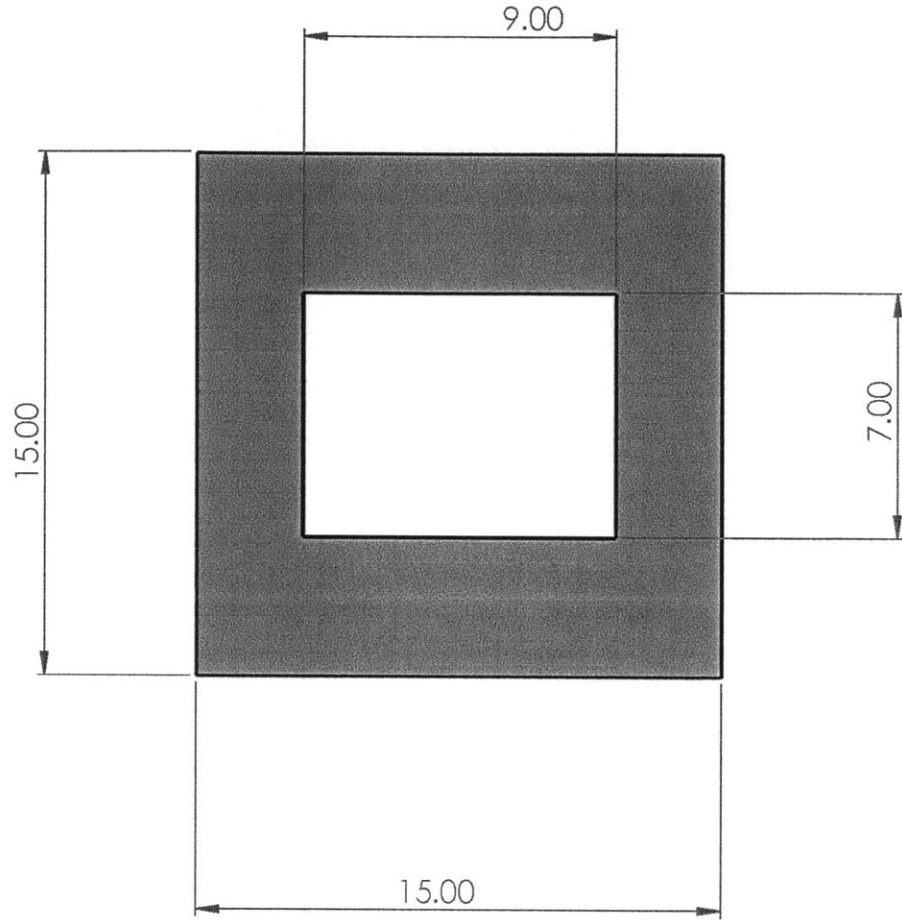




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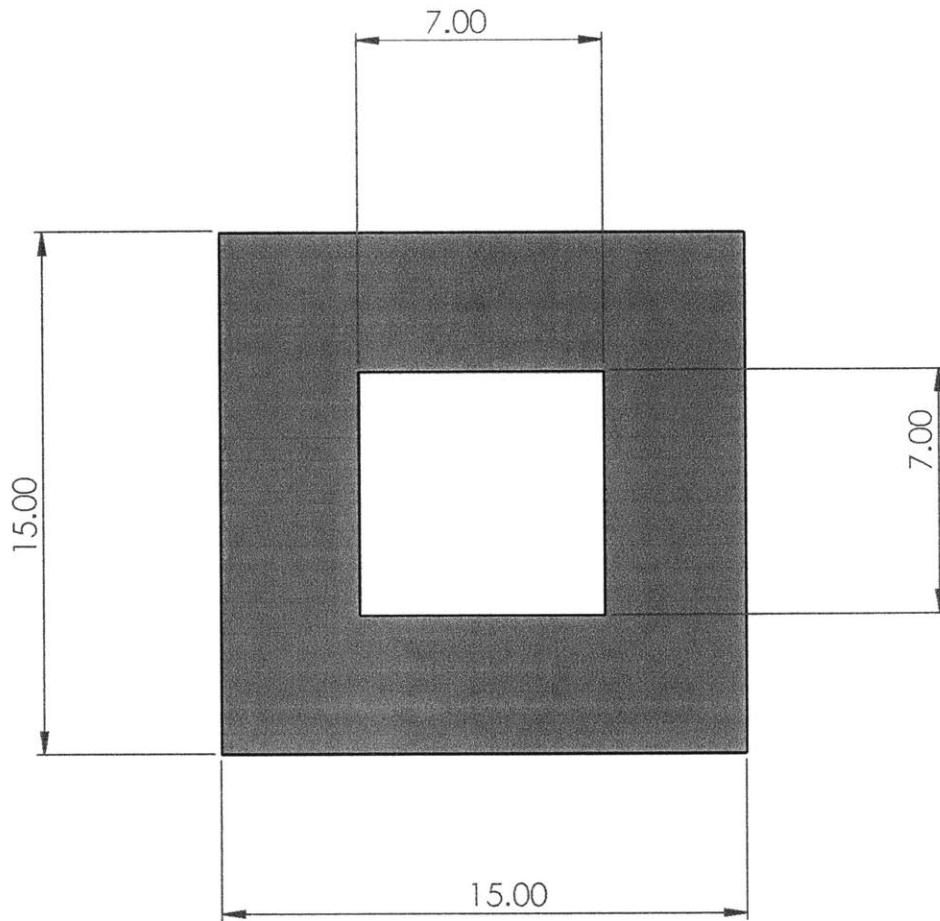
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:			FINISH:	DEBUR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION
DRAWN				TITLE:		
CHKD				DWG NO.		
APPV'D				15by15-oval1c		
MFG				A4		
Q.A				75		
WEIGHT:				SCALE:1:10		SHEET 1 OF 1

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DRAWN			SIGNATURE		DATE		TITLE:				
CHK'D							<b>SolidWorks Student Edition.</b> <b>For Academic Use Only.</b>				
APP'VD											
MFG											
Q.A											
							DWG NO.		A4		
							15by15-rec2c		76		
							SCALE: 1:10		SHEET 1 OF 1		
							WEIGHT:				





UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS		FINISH:		DEBUR AND BREAK SHARP EDGES		DO NOT SCALE DRAWING		REVISION	
SURFACE FINISH:									
TOLERANCES:									
LINEAR:									
ANGULAR:									
NAME		SIGNATURE		DATE		TITLE:			
DRAWN									
CHKD									
APPVD									
MFG									
Q.A						DWG NO.		A4	
						15by15-square1c		77	
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						WEIGHT:			

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DWG NO. 15by15-square1c

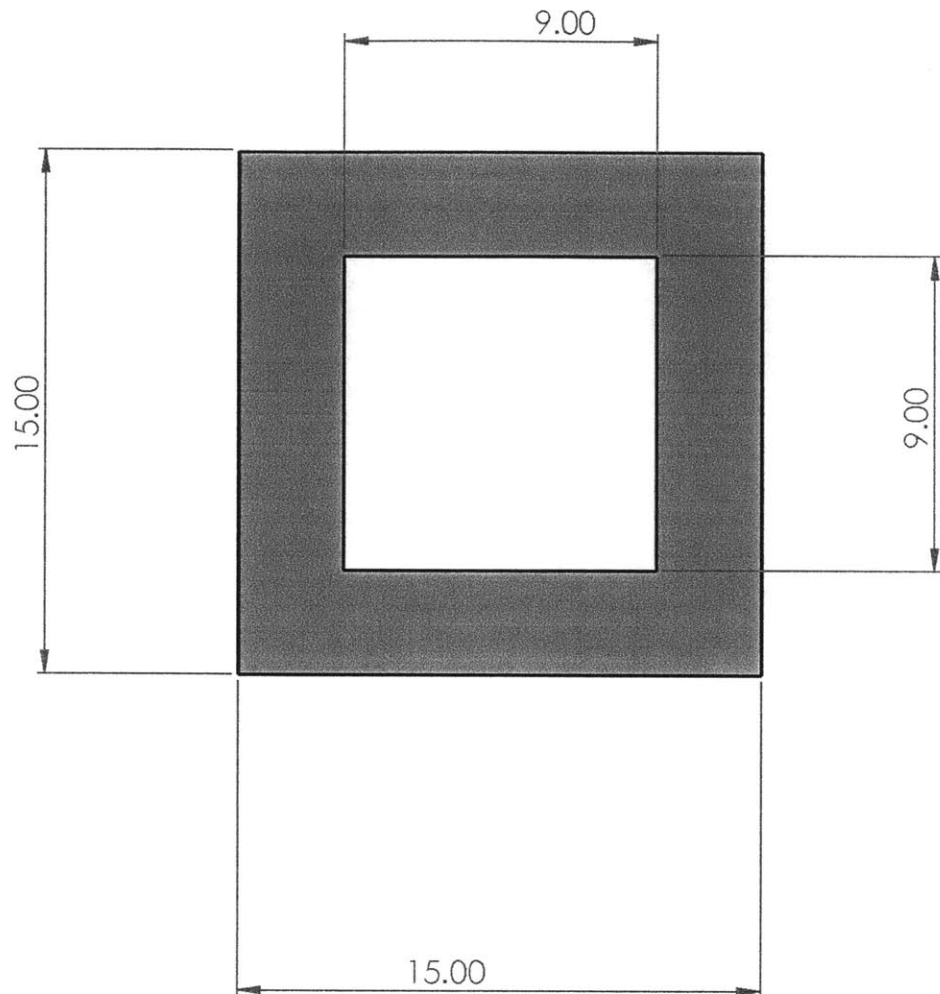
A4

77

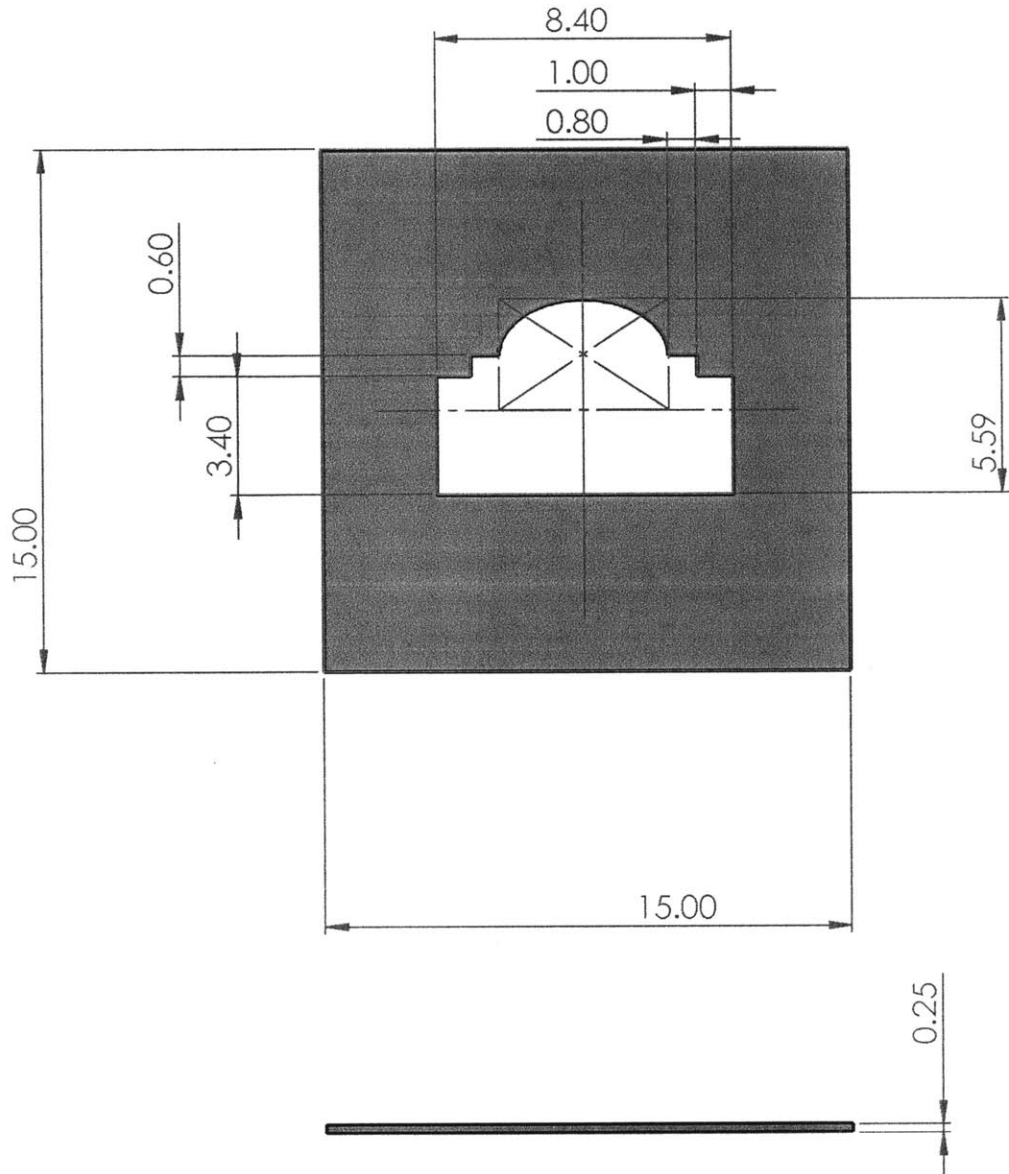
SCALE:1:10

SHEET 1 OF 1

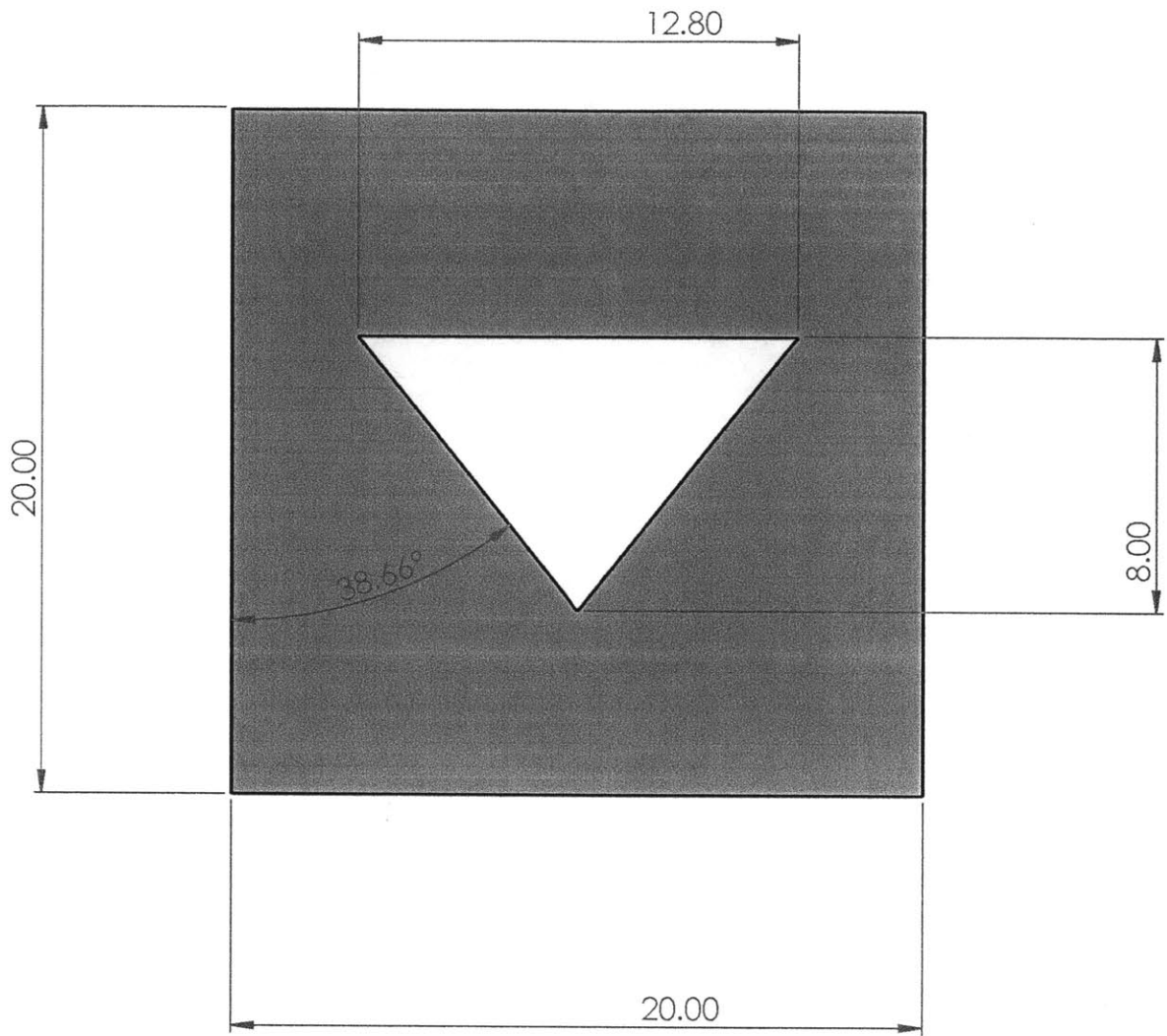
WEIGHT:



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:		FINISH:	DEBUR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION
NAME	SIGNATURE	DATE		TITLE:	
DRAWN					
CHK'D					
APPVD					
MFG	<b>SolidWorks Student Edition. For Academic Use Only.</b>			DWG NO.	15by15-square2c
Q.A					A4
			WEIGHT:	SCALE:1:10	SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:			FINISH:	DEBUR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION
DRAWN				TITLE:		
CHK'D				DWG NO. 20by20-dome2c		
APPV'D				A4		
MFG				SCALE: 1:10		
Q.A				SHEET 1 OF 1		
SolidWorks Student Edition. For Academic Use Only.				79		
WEIGHT:						



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 DIMENSIONS ARE IN MILLIMETERS  
 SURFACE FINISH:  
 TOLERANCES:  
 LINEAR:  
 ANGULAR:

FINISH:

DEBUR AND  
 BREAK SHARP  
 EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APP'VD			
MFG			
Q.A			

TITLE:

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DWG NO.

20by20-tri1c

A4

80

WEIGHT:

SCALE:1:10

SHEET 1 OF 1

## Appendix C: Sample G-Code

(PROGRAM NAME - SAMPLEGCODE)  
( 1/4 STRAIGHT BIT TOOL - 1 DIA. - .25)  
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N110S18000M3  
N120G0G90X14.9651Y87.3054Z2.  
N130Z.1  
N140G1Z-.25F100.  
N150X14.9612Y87.419F200.  
N160X14.9498Y87.5281  
N170X14.9309Y87.637  
N180X14.9044Y87.7457  
N190X14.8701Y87.8542  
N200X14.8279Y87.9622  
N210X14.7778Y88.0698  
N220X14.7196Y88.1768  
N230X14.653Y88.283  
N240X14.5781Y88.3881  
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N260X14.4026Y88.5942  
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N370X12.8369Y89.5101  
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N490X10.4103Y89.6813  
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N510X10.0083Y89.6038

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N530X9.6265Y89.4985  
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N760X7.535Y87.3065  
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N780G1X6.255  
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N820Y81.0347  
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N850X16.37  
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N880X15.09  
N890G2X14.9651Y87.3054I0.J.125  
N900G1Z.1F100.  
N910G0Z2.  
N920X1.25Y94.8747  
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N1200X42.4099F200.  
N1210X42.3899Z-.25  
N1220X37.0212  
N1230X37.0012Z-.23  
N1240X36.0412  
N1250X36.0212Z-.25  
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N1270X31.0074Z-.23  
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N1300X30.9741Y87.5416Z-.25  
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N1320X36.4502Y80.6965Z-.23  
N1330X36.75Y80.3217  
N1340X37.0499Y80.6965  
N1350X37.0624Y80.7122Z-.25  
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N1370X42.5901Y87.6218Z-.23  
N1380X42.8899Y87.9966  
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N1400G0Z2.  
N1410X26.75Y94.8747  
N1420Z.1  
N1430G1Z-.25



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N1490G2X26.625Y74.7497I0.J.125  
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N1510G2X26.75Y94.8747I.125J0.  
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N1530G0Z2.  
N1540X45.125Y67.6247  
N1550Z.1  
N1560G1Z-.25  
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N1580Y63.8747  
N1590X45.125  
N1600Y67.6247  
N1610Z.1F100.  
N1620G0Z2.  
N1630X37.25Y70.3747  
N1640Z.1  
N1650G1Z-.25  
N1660X46.25F200.  
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N1700G1X37.25  
N1710G2X37.125Y61.2497I0.J.125  
N1720G1Y70.2497  
N1730G2X37.25Y70.3747I.125J0.  
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N1750G0Z2.  
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N1770M30