# Claybot V2.1 Introductory Guide

# TABLE OF CONTENTS

# INTRODUCTION
## How Claybot works for Educators

Claybot has been designed for educators. Our aim is to make the teaching of 3d printing so much more accessible to educational establishments by using the unique material that is clay. Thinking about and working with clay enables a wide spectrum of creativity whilst also demanding the knowledge discipline and practical application of 3d-design and modelling.

Printing with clay is safe. There are no obnoxious consumables to deal with like plastics, powder and waste gases that arise from traditional desktop 3d printing. The clay used is in its natural state – nothing is added beyond normal clay ingredients and water.

Clay prints are also so much faster. Nozzle sizes vary from 1mm to 6mm, extruded at a rate of up to 50mm per second – so delivering up to 1.5cm$^3$/sec. Your objects appear in minutes and not the hours that printing with ABS and PLA plastics require.

Clay objects can be worked after being printed. This is simply not possible with plastic 3d-objects since they are fused solid in the printing process. Post-print is definitely where art takes over from the science. The satisfaction and beauty of working clay and glazing or painting its surfaces remains true to the artform.

Of course you may also choose to produce only to the greenware stage and use Claybot as the fastest, most environmentaly friendly and most efficient way to demonstrate the principles of 3d printing to your students. You can show students a 3D file, explain how a slicer works and show them the GCode that makes the 3D printer move. Using Claybot, complex technology systems can be explained in the most elegant and fun way.

## For Lessons. For Extra-Curricular

Claybot applications vary widely depending on the institution and the teaching champion behind its introduction. Educational budgets get ever tighter – and certain areas like the arts are always under pressure despite the widely held opinion of the need for expansive, creative thinking.

There are schools considering the integration of Claybot in a cross-curriculum type way e.g. design & technology led projects that bridge across into art. Other schools see such equipment as fulfilling an interesting role in extra-curricular clubs and learning classes – where students who wish to go beyond the introductory basics choose to push their knowledge and the boundaries of what is achievable, free from the confines of lesson-lecture time.

## Excite your Students and the wider Community

There is nothing more mesmerising than watching a deltabot robot create a unique, 3d-printed object.

The metronomic action draws the observer in as the object emerges, seemingly from nothing. This is additive manufacturing and appears completely different from the subtractive and manipulative processes we are more familiar with (e.g. machining a metal or wooden block or throwing a pot).

A working Claybot is an attention grabbing focal point during community open days. Witness visitors, both young and adult, go wide-eyed when introduced to something entirely new. Fascination and excitement abound when they see how technology and creative arts can be fused to offer a freedom of infinite creative possibilities.

## Claybot: Benefits & Considerations Summary

# BENEFITS

- Clay prints are relatively fast.  Nozzle sizes vary from 1mm to 6mm, extrude at a rate of up to 50mm per second – and so deliver up to 1.5cm3/sec.  Layer thicknesses from 0.5mm min.m.
- Clay is a natural material that can be quickly recycled for use in its original form.  No obnoxious gases or waste product.
- Works with freely available softwares for 3d modelling and 3d-print preparation  e.g. Fusion360, Blender, Slicr
- Free 6 week trial allows you to experience directly how Claybot might work for you and your community.
- Bigger objects output quickly with clay.  Demonstrate the fundamentals of 3d-printing elegantly in ideal classroom timeframes.
- Build envelope 200 diam. x 300mm height. Keeps volumes sensible for kilns and clay material costs in education.
- Cross-pollinate STEM subjects with art to make STEAM !
- Clay allows experimentation with other input variables like sound & colour pigmentation.
- Post-print processing capability.  Work dries like any ceramic object – over 2-4 days – from soft to medium to leather-hard allowing further sculpting & modelling.
- Post-print decoration and glazing add a whole other exciting discipline.
- Acrylic paints can be used to decorate bisque-ware, saving a 2nd glaze firing.
- Monthly financing available for £2940 purchase price
- Clogging at print-head is rare.  Easily free clogs by cleaning with water.
- Minimal infrastructure required, just 2 power sockets.
- No compressed air, 3 phase electricity supply or special ventilation required.
- Claybot utilises OpenSource software and firmware
- Cartridge swap-out service :– provides convenience, saves time and ensures clay consistency.
- Cartridge refilling on-site, by hand is possible and a cheaper alternative than swap-out service.
- Scanned objects/artefacts make for good project starting points.
- A working Claybot is an attention grabbing focal-point during community open days.
- UK company for support & service.

## CONSIDERATIONS

- The softness/plasticity of printed clay must be anticipated. Good design will embrace this property.
- Clay is a predictable material but can be messy when wet or dust-dry if used chaotically.
- Solidworks, available in many schools is suitable but other softwares may be better for organic form modelling.
- Prevalence is to print bigger 3d-pieces in clay. Despite its low cost per piece price needs to be controlled.
- Build volume may not be ideal for some out-sized pottery ambitions.
- Overhangs in designs should work within the guideline: no greater than 20º from vertical.
- Some ceramics expertise is required to get full benefit of the glazing process.
- Bisque ceramics can be painted in acrylics if food or water resistance not necessary.
- Price is comparable to a robust, plastics 3d-printer
- Kiln firing, either on-site or locally, is preferable if project opportunities are to be maximised.
- Opensource does not mean open to abuse. Risk of error/fault introductions by over-confident dabblers should be assessed.
- Cartridge swap-out service incurs an average raw material price of £2 per kg
- Cartridge refilling by hand requires time, effort and clay will likely be less consistent throughout.
- Clay detailing to 1mm will preclude 3d-models designed for production with plastic filament printers.
- Surface space is required to dry multiple pieces.

# Set-Up and Installation

## Step 1

Parts supplied include:

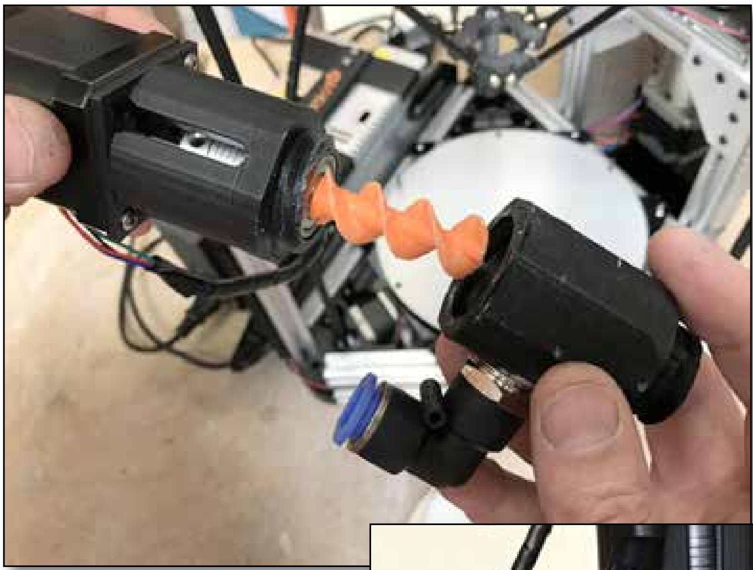
- 2 Nozzles, 2.5mm and 3.5mm
- Stepper Motor/Casing
- Spiral Auger
- Auger Chamber
- Nozzle Holder
- Chamber Blanking Disc
- Elbow Connector
- 2mm allen key, Sewing machine oil (for lead screw at weekly intervals)

## Step 2

Insert Spiral Auger into the Stepper motor coupling.

## Step 3

Tighten up the bottom grub screw onto the Spiral Auger shaft using the Allen key. Access through the slots in the Stepper motor casing. Repeat for the 2nd grub screw at 90 degrees to the first.

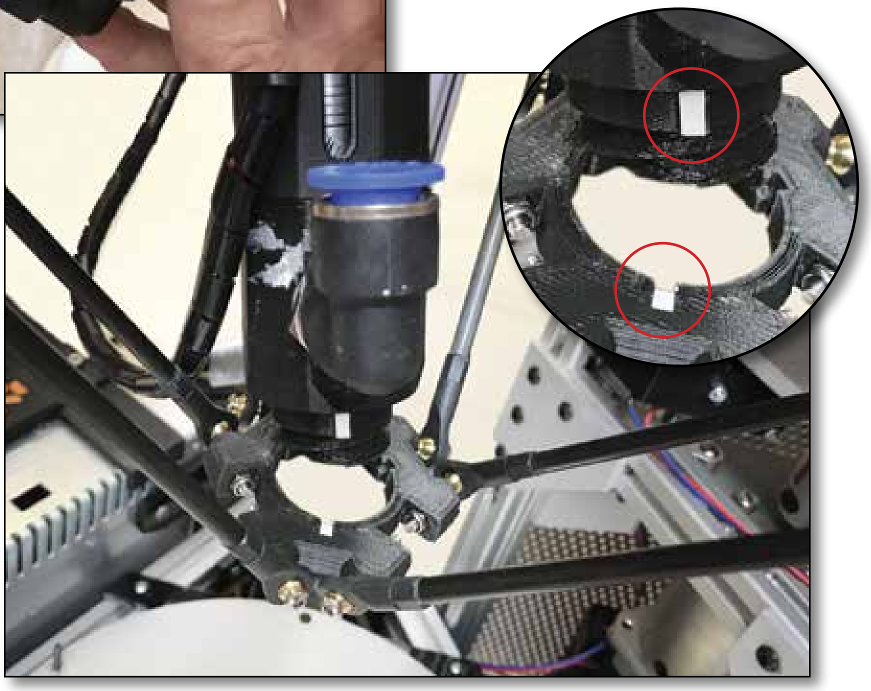


### Step 3

With a screw action - fix the Auger chamber onto the Stepper motor casing.

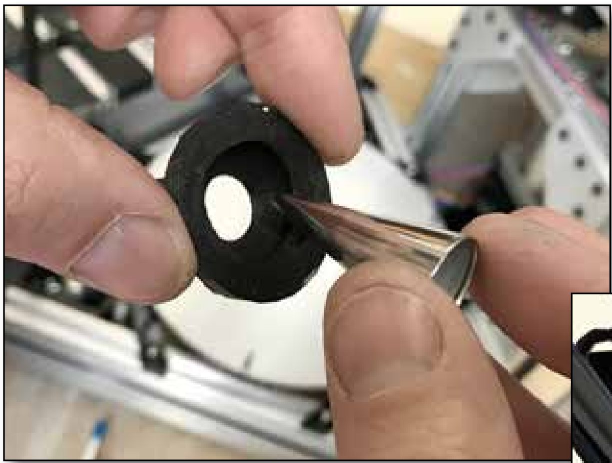
### Step 4

Use the three locating tangs (marked in white in photo) to mount the Stepper/Auger assembly onto the Deltabot carrier at the centre of the robot arms.



### Step 6

Select one of the nozzles, either 2.5 or 3.5mm.



### Step 7

Place your nozzle through the nozzle holder.

### Step 8

With a screw action - fix the nozzle/nozzle holder to the bottom of the Stepper/ Auger assembly from below the Deltabot carrier.

### Step 9

The completed Secondary Extruder of your Claybot.

### Step 10

Clay Cartridge assembly consists of: Clay cartridge, Elbow connector, Teflon tube with end-cap.

## Step 11

Clay Cartridge assembly consists of: Clay cartridge, Elbow connector, Teflon tube with end-cap.

## Step 12

Screw the cartridge to the threaded mount of the Primary Extruder of Claybot. Firm but not tight is a good rule of thumb.

## Step 13

Insert the free end of the Teflon tube. Make sure it locates into the connector with a definitive push where you feel resistance.

## Step 14

Remove the Teflon tube end-cap by retracting the blue plastic flange. Note this may be difficult after printing clay and may require open pliers rather than finger-pull to enable release. If still difficult, soak in water for a few minutes.

### Step 15

Connect the open end of the Teflon tube to the connector in the Auger chamber.  Again make sure fit is firm and rotate the elbow to ensure tube does not interfere with Deltabot arms operation.

### Step 16

Open the app Repetier-Host on your tablet.

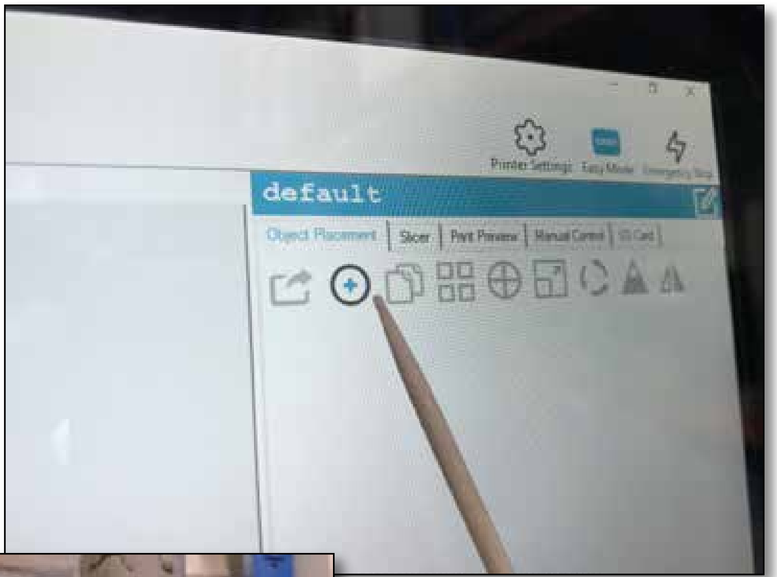


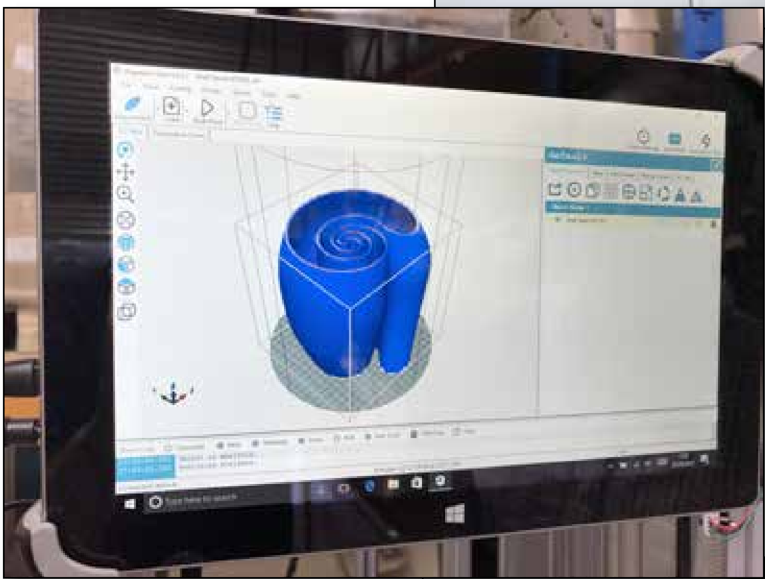
### Step 17

Connect the software to Claybot. When selecting tablet commands there is sometimes a delay before action occurs - it pays to be patient for a couple of seconds!

## Step 18

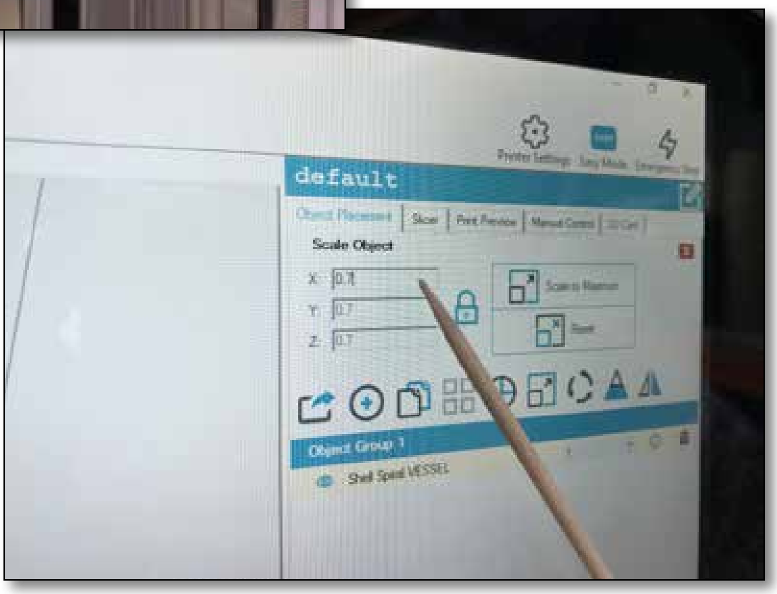
Select an object for printing using the 'Object Placement' tab and browsing using the + button.



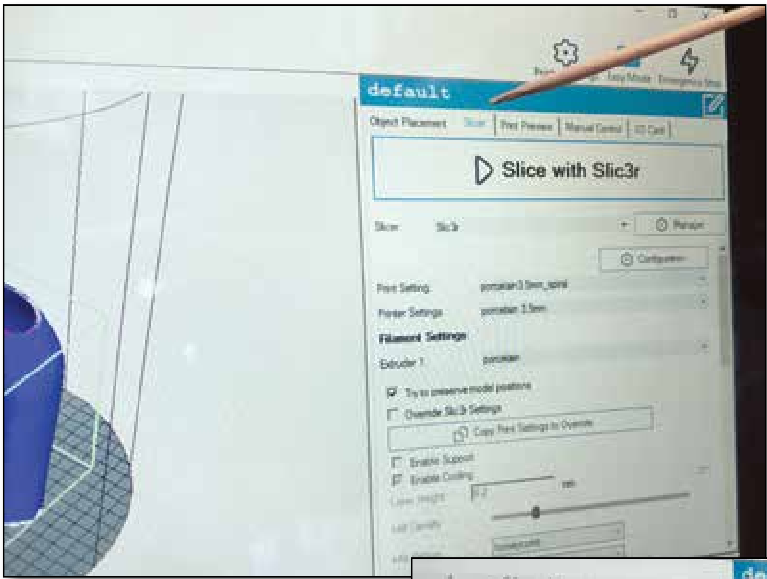
## Step 19

The file should be an .stl file which all 3d modelling softwares can export. The object will appear to size in the virtual print window of the Claybot envelope.



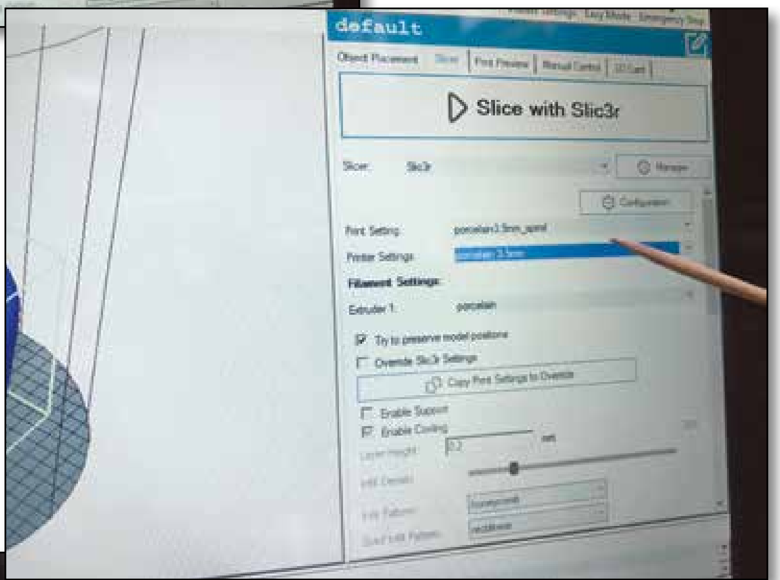

## Step 20

Often it will need scaling to a more suitable size. Use the Scale icon to change object size - where if you adjust one axis the others will automatically update.



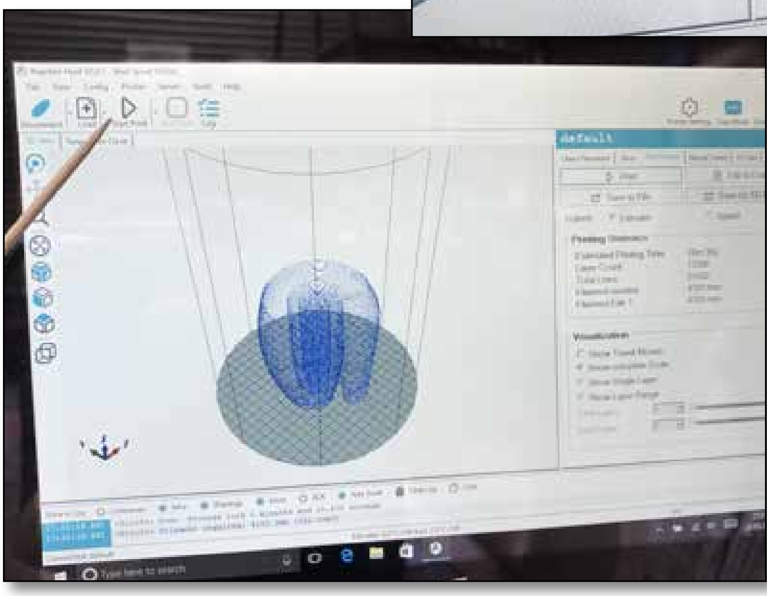

## Step 21

The 'Slicr' tab is used to break your object down into layers and Gcode which the printer will understand. Again - the tablet takes time to calculate commands - but the 'Slicr' tab will open when ready.




## Step 22

Select some suitable Presets from the dropdown menus - matching Nozzle size, with Clay type and Print Settings.




## Step 23

When complete - a virtual 'sliced' representation of your model appears in the print window.

'Start Print' will initiate the Deltabot trace to your model.



## Step 24

The operation of the Deltabot - using presets but also with adjustments in the 'manual control' tab - must be compatible with a suitable clay throughput. The Directional switch is pressed up for clay compression, thus increasing the pressure on the plunger inside the cartridge. Switch down to release pressure and draw the pushing piston downwards.

## Step 25

A setting around 4 is a good starting point for soft clays like the Claybot stoneware mix.

Harder clays may require more power. But at all times if rotation of the Auger ceases at the Secondary Extruder (seen by grub screws passing the chamber slots) - then the clay is not flowing as smoothly as it should. Trying to push clay that is too hard (if the mix is wrong or has stood for too long or been open to the air) can cause machine damage. A sympathetic ear will tell you that the machine is under too much strain. It is better to back off - clean the auger assembly and perhaps try a new cartridge.

# Claybot FAQs

## ENQUIRIES for FREE TRIALS & HOW TO ORDER

Without doubt, the Claybot team wish you to be completely at ease with how Claybot is going to work in your environment and how it is going to energise your students during your free trial.

Claybot is a product in demand and depending on the point in the academic year may have a delivery lead-time of between 2-6 months.

We understand an educational establishment works on an annual budget cycle and demands proposals that must demonstrate huge value to their community. Our 3d Print in Clay – Pros & Cons PDF may help in this regard. It is drawn from the experience of users in educational environments.

## CLAYBOT & ACCESSORIES - PRICING

Claybot is virtually an out-of-the-box piece of equipment. Usually it is delivered to you by one of the Claybot team and they will install, set-up and test print for you.

Your Claybot is delivered with 3 x 4kg primary tank cartridges filled with Stoneware clay. You will also receive a minimum 2 hours of on-site set-up and training.

Price: £ 2940

Monthly financing is available for one or more Claybots purchased.

Delivery to overseas customers by international courier will be supported with a series of face-time /webinar sessions to help you through the initial stages if required.

4kg Clay cartridge – Stoneware Clay £ 8 ea. (includes delivery as part of a bundle of 6)

4kg Clay cartridge – Porcelain Clay £ 12 ea. (includes delivery as part of a bundle of 6)

Choose any combination to make a bundle of 6 cartridges.
{Order here / tel: 0808 178 9869; customersupport@claybot.co.uk}

(You may choose to refill your cartridges with your own clay supplies. But please be aware of the time and risk this places on your shoulders. Refilling cartridges is time consuming – and should your clay be ill-prepared, operation of your Claybot may be compromised).

Our cartridge swap-out service is for multiples of 6 cartridges – 6 delivered in, 6 taken away.

Please retain your packaging boxes if possible to aid you in this service.

## Upgrades and Spare parts (out of warranty period):

Clay Cartridge (82mm ID x 460mm inc. end caps)  £ 42.50

Print-head Auger (plastic)  £ 35

Primary extruder motor & gear  £ 235

Print-head motor  £ 137.50

3.25" or 82mm Pugmill-Cartridge Adapter  £ 65

Additional Printing Bats -  £ 7.50 each

Printing bats supplied with your Claybot are made from moisture-resistant plywood.  They are slightly porous so your objects will release easily from the surface as they absorb water from the clay.

## HARDWARE  DETAILS

### 01. *What materials are used in the Claybot ?*

Aluminium and chrome are used for the moving parts and support rails of Claybot.

Steel and 3d printed PLA make for brackets and holding clamps.

The 220mm diameter printer bats are made from moisture-resistant ply. This material is best for 3d clay object adhesion, is water-proof yet porous and so releases objects easily.  You can make your own bats to this template or purchase additional ones from us.

Claybot cartridges are made from 4mm walled clear-acrylic with white PVC end-caps.

### 02. *What power supplies are required?  What current / voltage does it run on?*

The printer uses a standard Power Supply Unit and works with mains voltage supply of either 110 or 240V at 50-60Hz.  This is used to drive two stepper motors, running at 12V and 36V respectively. They draw a current below 4A.

Two standard power sockets are required in close proximity to your Claybot.

### 03. *What else do I need on-site to operate Claybot successfully?*

Not much !

Most of your infrastructure requirement will depend on your intended Claybot application(s)  [see 'How Claybot works for Educators']

Access to a potters kiln the size of your build volume if you wish to bisque and glaze fire.

In addition, if you plan to refill your own cartridges you will need a pugmill and some time for preparation.

A greenware drying area is also required –its size depending on the planned throughput you expect to achieve.

There is NO need for compressed air, 3 phase electricity supply or special ventilation.

### 04. *Is your hardware/firmware opensource?*

Claybot has been designed to offer optimum capability for its constituent parts.

In essence, it is a machine of parts which can be adjusted or swapped out for other parts. But the interaction between drivers, motors, firmware and software is sensitive. That inevitably means should customers choose to dabble with their Claybot's design and part specification, their warranty will be invalidated.

The Claybot CPU is designed around an Arduino Uno R3 setup.

### 05. *Controlling the variable which is Clay…*

The standard mixes of stoneware and porcelain clays should be suitable for all object sizes printed within the Claybot envelope. These reach a maximum height of approx. 300mm and diameter 200mm.

Where the danger of drooping under gravity is a possibility (due to design overhang) the effect can be marginally reduced by artificially drying the printed object as it emerges. Future Claybot versions are planned to have flexible, orientable fans for this purpose. But any air-drying jet focused just below the current printing layer will suffice. Move as necessary as your object becomes larger.

A harder, less plastic clay mix gives better wet strength but increased friction in the extruder systems. This may result in inconsistent clay delivery at the print-head.

### 06. *3d Clay Bats*

Printing bats supplied with your Claybot are made from moisture-resistant plywood. They are porous so your objects will release easily from the surface as they absorb water from the clay.

Bats will last almost indefinitely if well maintained. For best results, sponge a little water onto dry, porous bats before use. Clay should be sponged off before it dries to avoid dust. Store bats on edge to avoid trapping moisture.

You can use your own bats which will need securing to the Claybot baseplate using the pin locators and/or squashing marble-sized clay pieces around the edges. Plastic bats are nonporous and waterproof , so they will require wire-off for your objects. Plywood is a durable bat material but must be exterior- or marine-grade to avoid delaminating.

### 07. *Is there a maintenance schedule?*

Every Claybot is supplied with a maintenance chart and checklist to follow.
But in short, it is simply a good habit to clean your Claybot at the end of each printing day in preparation for its next use.

It is also advisable to back off the pressure from the plunger at the end of the day (see Control Tablet interface) or before storage for a day or two.

Clay should never be left open-to-the-air at the print-head and primary tank connection points.

It is acceptable to leave part-full primary cartridges in place for a few days if not under plunger pressure – but consider removing completely from your Claybot if that period is to be longer.

Use a damp cloth to remove clay water seepage from the base and metal clamps and rails.

Motor drive belts should be checked every 4 weeks for signs of wear and that belt tightness has not deteriorated.

The Delta arm supports and extruder guide rails should be first cleaned with a damp cloth, followed by a clean, dry cloth and finally greasing of the joints with petroleum based grease.

### 08. *Warranty Cover*

Claybot comes with 12 months warranty on parts - excluding consumables.

We do not cover damage from electrical surges or accidental damage due to physical force or excessive heat.

Seizures caused by lack of routine cleaning and lubrication may be recoverable using our 6-step Recovery protocol. But no guarantee is offered as to the outcome and parts may need replacing at the customer's expense.

Damages to the touch screen caused either by excessive force or corruption of the firmware are not covered under our warranty.

You will find a more comprehensive description about coverage in the Terms of Sale you receive with our pro-forma, invoice or quote.

## GENERAL OPERATION & TROUBLESHOOTING

Claybot is designed to be as trouble-free as possible in the conditions normally present in an educational environment. But printing with clay has the feel of art-meets-science.

Clay and people introduce variables which can sometimes be difficult to control or predict.

If your issue is not covered in the list below, just email us for extra help: customersupport@claybot.co.uk

### 01. *Is there a video I can watch on how to set-up my Claybot ?*

Yes – find it at: www.claybot.co.uk/setup or YouTube.

### 02. *The clay cartridge plunger is not moving*

If this is the first time you are using the printer, check the cables to the base motor. If you have just cleaned your Claybot check if clay or other particles have crept between the cable connector.

If that does not solve the issue make sure the cables are connected in the correct slots.

Remove primary cartridge and check clay has not hardened over time and become impossible to push.

### 03. *My print-head auger is not turning smoothly*

Clay is very abrasive. When it dries it will turn hard like stone.

The top part of your Auger is smooth and also acts as a seal. If dry or stiff Clay congregates in this area then auger rotation will likely be impeded. In addition to the prescribed maintenance routine – and depending on the hardness of the clay you are trying to extrude – you may find spraying the top part of the auger (where it meets the motor connection) with WD40 as it prints helps to keep the equipment free from clay build-up.

Does the print-head auger turn when the print-head is removed from the machine?

If not then it is likely hardened clay has accumulated in the auger chamber and it will need cleaning out with water and brushes.

### 04. *Achieving a solid bottom layer*

When you are printing an object that needs a solid base it is best to print this. It should be part of your 3d-model although the 3d-Slicer presets make adding a base an option for you.

A solid base can be added post-print (hand-work or casting). But care must be taken to use clay of the same mix and wetness to avoid differential shrinkage cracking where the base joins the walls of your 3d-object.

### 05. *My print layers are not lining up properly.*

Initial advice is to print more slowly. While it's possible to print up to 50mm/sec, the mass inertia of the print-head can cause print problems where there are sharp angles and breaks in the design.

Only rounded or organic shaped forms without infill can be printed at fast speeds. We always recommend to start slowly and gradually increase speeds. Remember to lower the speed gradually again as the print nears its end point for a neat finish.

### 06. *The print-head is not moving smoothly (or at all)*

Check the belt tension. If it's too low, remove the belt end-loop from the vertical carrier and shorten a fraction. Re-attach the loop to the carrier.

Check the teflon tube is not fouling the belts or deltabot arms when they are trying to move.

If a stepper motor has seized, it may need replacing.

### 07. *How do I clean and service my print-head extruder?*

Follow these steps to fully service your extruder. (see website video). If clay build-up or small hardened lumps are the problem, then water immersion along with a suitably sized brush should be all that is needed.  Oil with WD40 and grease the moving parts as you reassemble.

For times when the print-head extruder is completely stuck, disconnect the print-head from your Claybot and lower it into a glass with water.  Make sure the upper half of the auger clamp and the motor above are not submerged. Leave it to soak for about an hour. If that does not work follow the steps to dismantle the extruder for cleaning.

### 08. *The Primary extruder stutters or halts randomly!*

There are multiple reasons this may occur, but clay hardening & cleanliness in the system are root causes.

Refer to cleaning instructions for the complete primary cartridge and print-head extrusion system.

It is possible the primary plunger is getting stuck inside the clay cartridge tube.  This is usually when clay has hardened in the tube under compression or time. Occasionally excess clay settles between the O-rings, hardens and causes drag between the plunger sides and the tube sidewalls. The plunger can be removed by reducing piston pressure, then loosening off the centre bolt-head sufficient for the O-ring seal to be released. Remove the plunger from the cartridge through the threaded end-cap, keeping its 3 parts together.  Soak and clean with water before reversing the procedure when re-inserting.

Excess clay may also get drawn into the lead-screw housing and eventually settle in the lead-screw end-bearing. Clay inevitably dries out over time and hardens like stone - causing disruption to moving parts.  Preventative maintenance such as cleaning and greasing the plunger push rods will minimize this problem.

The primary cartridge motor is designed to have plenty of torque at low speeds. The design of the Claybot, with a primary and print-head extruder, helps reduce inertia of the printed clay at the point of delivery. This allows better control of start-stop sequences in some 3d-clay models. However, if start-stop sequences are resulting in odd print output it may be better to revisit the sliced GCode of the model. For example, perhaps a different layer thickness will give cleaner breaks or when combined with a slower printing speed.

The primary cartridge motor in your Claybot has plenty of spare torque capacity to get the plunger system moving again in normal operating conditions.   But if the clay is too hard, friction throughout the pipework and in the auger flutes may cause one or both motors to stutter or stall.

But note, if the clay is too soft, excess clay can ooze from the tip of the auger. This is a momentum effect caused after the motors have ceased stepping.

### 09. *I moved my Claybot and now it does not work properly ?*

Check the cable connections into the frame-mounted controllers and tablet.

### 10. *What materials can I print with?*

Whilst we recommend to print with stoneware clay to begin with, you can print virtually all clay types as long as they are smooth and without large grog particles or fibres.

The Claybot 'Viscosity test' is a simple method to check that your clay body is the correct softness and plastic enough to print with. More information on clay recommendations can be found at www.claybot.co.uk

### 11. *What happens if my cartridge runs out of clay mid-print ?*

If the Primary plunger reaches its end-stop your Claybot will also stop.

Using your Control Tablet, return the plunger to its base position.

Then, simply unscrew your cartridge and replace with a full one.

Re-apply pressure to the new plunger until clay starts to ooze from the end of the teflon tube.

Restart your print - unfortunately from the beginning. It makes sense to check you have enough clay in the cartridge to complete a print entirely.

### 12. *Is there any pre or post processing possible?*

All Pre- and Post-processing can follow standard pottery processes. After printing you can still shape or work the clay like any conventionally produced work.

Object parts such as handles and unsupported sections you left-out of your 3d model may be better added using slip and hand-moulding at the most appropriate point in the greenware drying process.

Fine pattern details, carving and sculpting can be carried out in traditional ways on your 3d printed pieces once they have achieved some dried strength & hardness.

### 13. *How fast can I print?*

Print-speed depends on many variables:

- the type of clay you use.
- the softness (viscosity) of the clay.
- layer width and height you choose.
- the design of the print.

Recommended print-speeds are between 20 and 30 mm per second for any layer height or nozzle width. Certain objects, particularly larger ones, may benefit from assisted fan-drying. This helps part-solidify the walled layers in order to support the weight above them.

Our community videos give you an indication of what to expect and where to be surprised.

### **14.** ***What is the precision /resolution of the Claybot?***

A good rule of thumb is to use a ratio of 1 to 2 :  e.g. lay down a 1.25mm layer height with a 2.5mm nozzle.

Very fine and soft clay can be printed as fine as 0.5mm layer when using a 1mm nozzle.

For larger 4-6 mm nozzles, better results are achieved with layer heights between 2 and 3mm.

The range of options to experiment with is wide. The control of print-head speed is another important variable which can alter prints.  You may prefer designs and speeds which allow the clay to deform in different ways.  And the opportunity to introduce outside forces like sound adds a further dimension.

Thick, multi-layered walls are not recommended unless some heavy, post-print processing (like sculpting) is planned.

### **15.** ***Is it safe to print with clay?***

Printing with clay is safe. There is no difference to the clay you 3d-print and the material used in any conventional pottery.  But safe operation still demands sensible practices regarding clay dust, possible skin irritation and wiping things in your eyes.

### **16.** ***My issue is not listed!***

Please send an email with your question to:
customersupport@claybot.co.uk

# 5 Simple Steps for Educators to begin 3d-CLAY PRINTING

## STEP 1: 3d DESIGN in EDUCATION

Use any 3d modelling programme that can output a universal ***.stl file.** Most should be capable of doing this. Indeed, there are some fantastic, freely available programs in addition to paid-for platforms.

3d modelling software well suited to the task include:

Solidworks; Blender; SketchUp; Fusion360; OpenSCAD; Autodesk 123D

### Student projects

A complete student class can be set a 3d-design project. We recommend some sensible tuition is made regarding the properties and nature of clay in its various phase states. Perhaps introduce some background regarding clay composition, plasticity and factors that affect viscosity and how and why cracks form within a structure. Advanced planning and production thinking is also necessary for objects with overhangs e.g. how can we support the structure or post-process the piece? And an understanding of clay deformation under its own weight may yield interesting outcomes beyond the scope of a pure 3d-computer model.

Different objects and subject matter can be assigned for mixed ability groups and there is a huge online library of items available as finished or as suitable starting points. The Claybot team has put together a small portfolio of test objects which can be used as primers for thinking and discovery about Claybot's capabilities and limitations.

Projects can be cross-curriculum and our community videos showcase a wide and growing variety. Egyptian, Roman and Greek artefacts make for good subject matter and ancient fossils are another area worth exploring. The Claybot start-up portfolio provides a few examples.

Scanning objects is another way to achieve a 3d model. A head or body part can be scanned easily and Claybot offers the hire of a professional 3d Scanning device on a weekly cycle for those labs or classrooms who would like to plan projects but do not have direct access to scanning equipment.

Enquire about our 3d scanner hire at: customersupport@claybot.co.uk

### Online 3d-models

In addition, there are some amazing online projects which continue to expand 3d-model content. **Scan the World** is a fabulous repository of 3d scanned artefacts from world renowned institutions and museums.

**Thingiverse** is a treasure-trove of freely downloadable objects that have been 3d-modelled by a community of 3d-printing enthusiasts. The majority of objects may not be suitable for printing in clay, but many are or can be taken as starting points for adaptation to work with clay characteristics.

## STEP 2: 3d PRINTING PREPARATION (3d-SLICER programme)

Download Slicr 3d as part of the Repetier-Host package. This is free and has great functionality. https://www.repetier.com/

Simplify 3D (License price approx. $150) is an alternative with some added visualisation features. https://www.simplify3d.com/software/

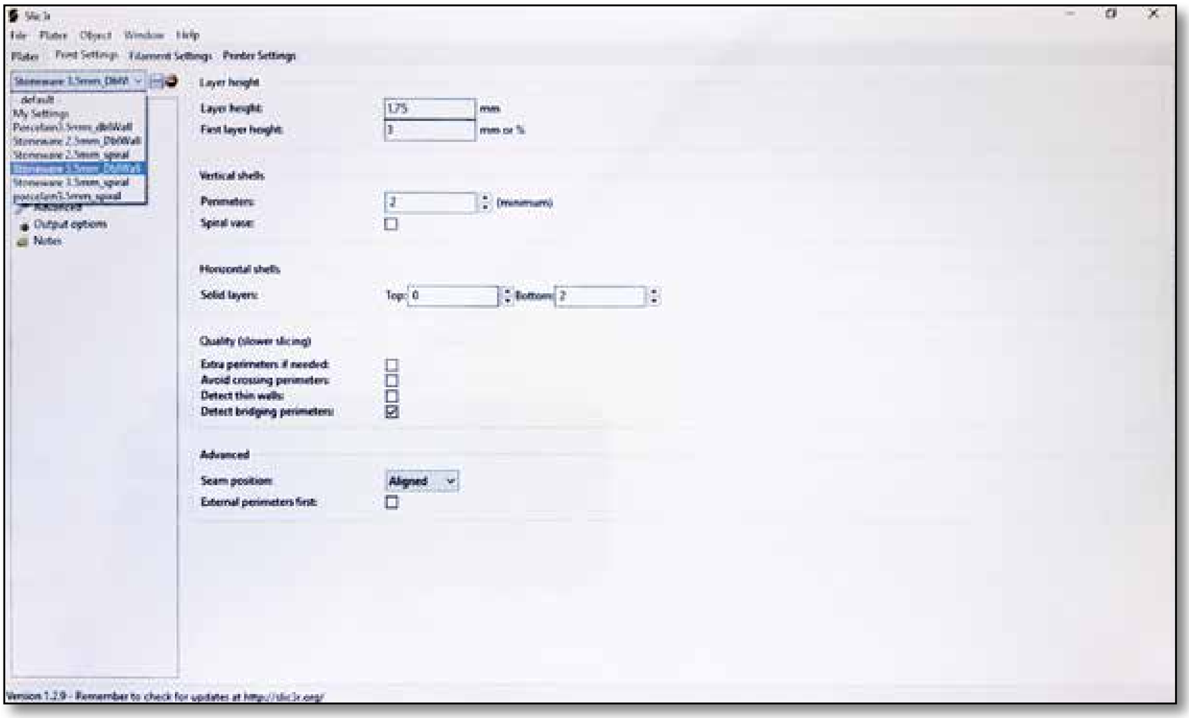
A Slicer programme allows you to import your *.stl files and convert them into printing instruction code

- for Claybot or any other 3d printer to follow. Your 3d-model is effectively broken down digitally into slices or cross-sections, based on the settings you choose. Settings depend upon the output material and your 3d-print machine characteristics. Amongst other things, your Slicer programme will tell you how much material will be consumed and how long your 3d-object is going to take to print.

This information is then neatly bundled into a GCode file which contains a stream of digital instructions to direct where, when and what the 3d-print-head and clay extruder will do.

The GCode can be delivered into the printer over a network, or by transferable SD card plugged into the Claybot Control Tablet.

## The key settings in a Slicer programme present on the 'Print Settings' tab:




**Layer height:** specifies the height of each slice or layer in your print. Prints made with thinner layers enable more detail to be achieved and keep the surface of your model smoother than the heavy ribbed look with thick layers. The downside to thinner layers, of course, is time to print. Typical layer heights for Claybot lie between 1.0 - 3.0mm. A nozzle diam/layer height ratio of 2 : 1 is a good starting point. E.g. 2.5mm nozzle - specify 1.25mm layer height.

**Shell thickness:** defines the thickness of the side walls and is one of the biggest factors in determining the strength of your printed clay object. If shell thickness is set larger than the nozzle size you are using in the print-head, then the print-head will need to trace the walls of your model more than once.

**Enable Retraction:** is a feature which tells the printer to stop the flow of clay when a break in the sliced layer of the print occurs. Retraction is usually always enabled, but is not necessary for continuous surfaces like many pots and vases.

**Fill Density:** Infill refers to the density of the space inside the outer shell of an object. It is specified as a % of the volume and usually prints as a grid like pattern inside your object. This is done to provide upper layers of your model with more support. If an object was printed with 100% infill it would be completely solid!

If you're creating an item for display, a minimum 20% infill is recommended. However, a vital point to remember with clay is to ensure there is always an open side to the infill cavities. They must not trap moisture – else the catastrophic perils of trapped steam in your piece when kiln firing!

To reduce weight post-printing – as your object and side-walls dry and become harder – you may be able to scrape some or all of the infill out of any cavity.


**Print-speed:** refers to the speed at which the print-head nozzle travels while it lays down clay. Optimal settings depend on the design, the nozzle size, the layer height and clay adhesion properties. The trade-off between high print-speed and lower quality is a personal one.

**Support type:** supports are structures that help hold up 3D objects where overhangs are present in the design. Printing clay throws up unique characteristics. Where plastics might accommodate up to 45 degree overhangs, clay in its wet state should be limited to 20 degrees at most, unless you wish to experiment with natural distortions under gravity. However, supports can be printed from the base on some objects

In the drop down menu, the only realistic option for supporting clay is Touching Build Plate meaning the support is built up directly from the base plate (Printing Bat). These can then be cut away at the appropriate dry-point as the object becomes leather-hard.

Initial layer thickness: is located in Advanced settings and refers to the thickness of your very first layer on the print bed (printing bat). With clay, a minimum base thickness of at least 3mm is sensible and most likely 6mm or more if your piece is large.

The option remains with some designs to fill base space after printing, using either a slab or slipcast.

## STEP 3: PRINTING YOUR 3D CLAY OBJECT

Claybot's Control Tablet has an intuitive user interface to help you pull the strings.

**Key Instruction 1:** Use Object Placement to position your piece. 'Scale' if necessary and then 'Slice' your object into printable layers.

**Key instruction 2:** Set the Primary Extruder speed control between 3 - 4 to achieve a good flow of clay.

**Key instruction 3:** Start a sacrificial print to check the clay is being laid down commensurate with your print-head speed. Adjust head speed as necessary on the Manual Control tab of Slicer.

After finding the calibration stops your print is ready to go. GCode from the Slicer program drives the movements of the Claybot motors and extruder print-head.

Fine tuning of your print can be done even while it's in process. Use the touchscreen to determine key parameters: print-head speed and ceramic flow from the nozzle. Begin with a slow print-speed setting and ramp up (along with increased clay flow) once your continuous print builds past the base layers.

It is also great to experiment with independent, outside influences on your 3d-printed objects. For example, the Claybot sound speaker demonstrates how to impart various effects DURING printing. Unusual print-speeds may give a poor result but just might give something uniquely different.

## The variable which is Clay…

The standard mixes of stoneware and porcelain clays in Claybot cartridges should be suitable for all object sizes printed within the Claybot envelope. These reach a maximum height of approx. 300mm and diameter 200mm.

Where the danger of drooping under gravity is a possibility (due to design overhang) the effect can be marginally reduced by artificially drying the printed object as it emerges. Future Claybot versions are planned to have orientable fans for this purpose. But any air-drying jet focused just below the active printing layer will suffice. Move the jets as necessary as your object becomes larger.

A harder, less plastic clay mix gives better wet strength. But increased friction in the extruder systems may result in inconsistent clay delivery at the print-head. A clay which is too plastic/wet/thin will not extrude properly through the pipe and print-head before uneven pressure forces cause inconsistent flows and mess at both delivery and primary tank ends.

You are welcome to experiment with a wide range of clay types as long as they are smooth and without particles or fibres. Claybot does offer a defined recipe for grogged clay (see Cartridge option 3) for which we also supply a particular print-head auger designed to cope with this highly abrasive material. But please note additional wear & tear in other parts of the delivery system are to be expected when compared to smooth clay-types.

For more information on clays, read our section **Understanding Clay**.

### Clay Printing Characteristics

Fast, successful prints depend on these key variables:

(i) type of clay and its prepared wetness (viscosity) ;

(ii) nozzle diameter & layer height (a ratio of 2 : 1 is a good formula)

(iii) design of the print-object (continuous curves vs stop-start and angles)

Recommended print-speeds are between 15 and 20 mm per second for standard layer heights (1-3mm) and nozzle widths (2.5 - 6mm). Interesting effects can be achieved by varying speed of head relative to the nozzle extrusion rate.

Very fine and soft clay can go as low as 0.5mm layer with a 1.0mm nozzle.

Multi-thickness walls are not recommended (it will double print times!) unless your object design demands a large degree of stability or heavy post-processing (like sculpting) is planned.

## STEP 4: POST-PRINT PROCESSING & SCULPTING

All Pre- and Post-processing of Claybot objects follow standard clay/ceramic practice. After printing you can still shape and work the clay like any other conventionally produced work. The state of the body evolves as the greenware piece dries prior to placing it in a bisque firing.

As an object air-dries it moves through these states:

(i) wet (newly produced) and not workable

(ii) Soft (damp surfaces)

(iii) Medium (inner damp surfaces – leather-hard outside)

(iv) Leather-Hard

(v) Bone-dry

It is important to remember that just because one section of your piece is in one state does not mean internal or wall intersections are in the same state.

The time it takes for drying to occur varies depending on design and environmental conditions. But in low humidity, ambient temperatures 20-30°C, this will take a minimum of 2-4 days and could be as much as 7-10. Depending on your project, you might choose to slow this further by wrapping all or parts of your object in polythene to prevent drying out in advance of adjacent sections.

At various points in the greenware drying cycle it may become judicious to imbue decoration to your object. A summary of the main techniques is provided below.

**Subtractive Decoration** involves removing clay from the surface of your 3d-printed object. This includes:

**Carving** – which may be done at any stage from soft to bone-dry. Although carving tends to be most satisfying when the clay is medium to leather-hard, gestural "smeared" effects are best introduced in very soft clay.

**Piercing** openings into a clay object may be preferable to attempting to print and support them in the wet state. Piercing is normally done at medium leather-hard stage with a hole-puncher or razor knife. However, it may also be accomplished at the leather-hard or bone-dry stage with an ordinary drill bit.

**Incising** usually refers to shallow carved lines or patterns using a dull-pointed dowel, or a dull pencil. Too sharp and you are effectively inviting cracks to form!

**Additive Decoration** is where clay is added to the existing surface of a clay form. In general, you should score the object surface and slurry all add-ons, except in sprigging. If the add-on itself is soft plastic clay, score and slip/slurry only the attachment point on the main form. If the add-on is leather-hard, score and slurry both surfaces.

**Appliqué** generally refers to preformed flat pressed or carved clay decorations added onto the surface of a piece.

**Sprigging** is pressing either small coils and/or balls of clay onto the surface. A thin coat of slip (without scoring) is adequate and is a nice way to introduce coloured contrast.

**Modelled** decoration includes a variety of methods when clay is added and then smoothed into the surface to create raised ridges, strips and pads. Sculptural manipulation with fingers and hands is then accomplished.

## STEP 5: KILN FIRING

*It would seem illogical to begin this section with a statement that says you do not necessarily need a kiln to get the main benefits from a Claybot. You can 3d-print, do post-print modelling and decorate with acrylic paints if your objects do not have to perform function (e.g. food and liquid tolerance). But they will remain very brittle.*

*If you are to uncover the true delights of glaze decoration and make your objects impermeable to water for functional purposes, then kiln firing is an absolute necessity. If you do not have one on-site, then perhaps there is a kiln in your school cluster where you can arrange access?*

In firing clay your objects are going to go through several chemical and physical phase changes. Our section **Understanding Clay** has more details but the key points are as follows:

**Free water evaporation** begins as soon as heat is applied to your 'air-dry' object. Even when water is only present as atmospheric humidity in bone-dry wares, never underestimate the power of steam. Any closed air pockets will trap steam that may cause blowouts or shattering as the pressure builds.

Beyond 220°C all free water has evaporated from the work. But chemically combined water is still present, so temperature increase must remain gentle. Each unfired clay molecule is attached to two molecules of chemically combined water, which makes up approximately 15% by weight.

At around 300°C organic materials begin to combust (oxidize). This includes organic contamination originally present in the clay, as well as bacteria which grows in the clay as it ages. Plenty of oxygen must be admitted to ensure complete oxidation of these volatile materials during the heat ramp to 500°C. This **water smoking** process continues until all water and impurities have been expelled by 850°C.

Around 500°C **sintering** begins. Clay particles begin to bond together - before the fluxes and silica start to form a glass. After this point the clay may no longer be returned to the plastic state.

At 600°C **quartz inversion** takes place. However, any expansion witnessed here reverses when the body temperature is taken back through this temperature during the cooling ramp.

900°C is your threshold minimum for a completed bisque-firing, when most clay particles have fused together.

Just above 1000°C (cone 06) needle-like mullite (aluminum silicate) crystals begin to form an interlocking structure. This glassy phase creates a combination of dense vitrification, great body strength, and a reinforced clay– glaze interface that is welcome in high-fired functional objects.

## STEP 6: DECORATION & GLAZING

If you do not have the time or experience to practice the intricacies of glaze colouring and thermal expansion tests, do not despair.

Clay which is bisque-fired can still provide a surface on which to decorate. And some sculptors even plan for this deliberately.

### Acrylics for bisque-fired pieces

Fired ceramic stoneware is very porous and will have a declared water absorption rate of between 2-5%, only being close to zero if porcelain. Use a flat spray paint or gesso to help seal the vessel and prevent paint being absorbed too readily. The beauty of this technique is that if you make a mistake or don't like the results you can simply re-spray and try again.

Acrylics are versatile paints in that they can be applied in washes like watercolours or used straight from the tube like oils. But they dry quickly – and unlike watercolours they dry permanent. That means you can paint over them without disturbing existing washes. However, they remain workable when in a wet condition (keep them damp in a bag between sessions!) and they clean up with water if necessary.

Sensible advice includes to remain frugal with your paint and water mixes. Tap your brush onto a cloth or paper towel to remove excess before touching it to your work. Get a feel for your brush and paint before you become bolder with your additions else problems like drips and blotches will be common. Mix colours on your palette and experiment on dummy surfaces like paper plates before your ceramic. Tints are created when you add white to a colour mix. Shades are created when you add black.

## Glaze decoration & firing

If you are making functional vessels, a glazed surface is required. It also provides opportunity to colourise your piece in a myriad of ways. Fired glazes are glass with various modifiers added to affect their behaviour and appearance. Whilst gloss is most prevalent, the surface may be engineered to be semigloss, semimatt, or matt. An average thickness coat of glaze is equal to three sheets of writing paper. And always glaze the inside first because you can easily wipe runs or drips from the unglazed outside with a sponge.

For bright contemporary effects, mid-range firing 1060-1240°C gives the ideal combination of good durability, is impermeable and offers broad colour possibilities.

Colour within, and on, a glaze surface is controlled by both clay and slip underneath the glaze working in conjunction with the type and amount of metallic colouring oxides and modifiers within the glaze. As in cooking, the recipe possibilities are immense.

The metallic colouring oxides are added to glazes in amounts typically ranging from 0.5% to 10% and generally will not affect physical properties of the glaze other than colour. The main colouring ingredients for slips and glazes are:

**Chrome oxide** produces green colours, except in combination with tin when it can produce pink. A reduction atmosphere (i.e. restricted oxygen) tends to blacken chrome oxide.

**Cobalt oxide** and cobalt carbonate are the primary blue colorants in ceramics and glass. Cobalt compounds are extremely powerful and are rarely used in amounts greater than 5%. With magnesium at high temperatures, cobalt can produce pink and red colours.

**Copper oxide and copper carbonate** produce green colours in oxidation, red in normal reduction.

**Iron oxide** is responsible for a wide range of glaze colours including green, yellow and brown. Orange and rust-red can be achieved when mixed with rutile.

**Manganese dioxide** is a weak colourant but is capable of producing a range of yellow to brown shades.

**Rutile** is a titanium ore containing iron, vanadium, and other materials. It produces tan in oxidation and grey in reduction atmospheres.

## Glaze Firing

When back in the kiln and put through a glaze firing cycle, your glaze will undergo a similar transition to the clay body in the bisque fire but to a different heat ramp profile: impurity gases are expelled, sintering of the glaze particles take place above 800°C and at just above 1000°C needle-like mullite (aluminum silicate) crystals begin to form an interlocking structure. This glassy phase creates a combination of dense vitrification, great body strength, and a reinforced clay– glaze interface, all of which we want in high-fired functional ceramics. This is where glaze fit i.e. when the shrinkage characteristics of the glaze match the clay vessel, is most crucial.

Around 1060-1240°C (cone 4-7) free silica in the clay and glazes that have not combined with fluxes to form a glass, begins to transform into **cristobalite** (crystalline quartz). This is an irreversible change. Note: Do not heat soak your piece above this temperature because this results in pieces susceptible to low thermal shock resistance.

As your glaze-fired piece cools the molten glaze passes from liquid to thermoplastic to solid an dis known as **annealing**. Throughout this process, the physical volume of the glaze and body change constantly, and rarely at the same rate. This is due not only to differing thermal expansion of the various materials, but also to the inversions of quartz (572°C) and cristobalite (260°C).

Whilst cooling stresses through these stages are usually comfortably dissipated in glass and ceramics there is a critical zone where cooling must be slow in order to accommodate and equalize differential shrinkage. For most glazes the critical zone extends from around 540°C down to 340°C, below the quartz inversion temperature. But note a porcelain glaze anneals at a temperature above quartz inversion and cooling ramps should be adjusted accordingly.

# The Beauty of CLAY

# The Beauty of CLAY

Clay is a wonderful material.  Natural, tactile, versatile.  Used throughout human history clay is all around us in both creative and practical forms. Yet increasingly, knowledge of its subtleties and characteristics is fading from the general population as its position in the arts curriculum has become harder to justify.

Claybot is a tool for educators to offer unique 'art-meets-science' cross-curriculum projects.  But in order to maximize the incredible possibilities that 3d Clay printing provides, a core knowledge of the characteristics of clay is crucial to enable successful production and post-production phases.

Clay for Claybot offers a quick summary for what you need to know to get reliable Claybot operation in short order.  But we recommend you explore the wider subject in our '**Understanding Clay**' section.

# Clay for Claybot

Various properties that occur in Clay are magnified under the conditions within the Claybot 3d-print system. In generating successful, different clay recipes the Claybot team aims to present educators with a system they can depend upon to deliver consistent results in the teaching environment.

The power of correct material choice is a combination of physical appearance, its mechanical properties and the solution it's used for. Our favourite and most forgiving is stoneware clay.

## 1. Claybot Recipe #1 - Mid-range Stoneware with fine Grog

It has the best interlayer adhesion and offers smoothest extrusion in the Claybot set-up. The addition of a fine grog (325 mesh) increases greenware strength and so improves workability post-printing.

Maccabee 90%. Ball clay X % . Bentonite 1%.

Allows good object overhang (typically 20 degrees from vertical) without slumping.

The offset of this recipe is greater wear of parts in the clay delivery system – particularly within the Print-head, Auger and Nozzles.

## 2. Claybot Recipe #2 - Porcelain

Interlayer adhesion can be more difficult with porcelain since the clay is short in comparison to stoneware. This means moisture can dissipate too quickly on a large print for the layers to stick together. For best results avoid high temperatures but keep humidity as high as possible.

Claybot cartridge's contain a 25 Porcelain recipe adjusted slightly with a small percentage of bentonite/veegum.

Complete greenware-firing cycle Shrinkage expectation is 15-20%.

## 3. Cartridge swap-out service

Our cartridge swap-out service is for multiples of 6 cartridges: 6 delivered in, 6 taken away. Each cartridge contains approx. 4kg of either Stoneware or Porcelain clay which produces for example, 18 standard mugs or equivalent.

The clay is prepared using a de-airing pugmill to a standard consistency known to maintain its plasticity properties for up to 4 weeks in a sealed and bagged Cartridge.

## 4. Cartridge refilling by Hand

You may choose to refill your cartridges with your own clay supplies. But be aware of the time and risk this places on your shoulders. Refilling cartridges is time consuming – and should your clay be ill-prepared operation of your Claybot may be compromised.

The standard approach is to add 1/20 water to clay by weight (e.g. 500gm to 12.5kg)

Cut a bag of clay into 4 similar pieces and put a microfiber towel between each section. Add the water and re-seal the bag ensuring it is airtight. The water will penetrate the clay in one to two days.

Remove the clay and begin manual wedging - adding very small amounts of water until the consistency is right. Compare your consistency using our 'Viscosity Test'.

With the screw-in end cap and plug-fitting removed from each end of the cartridge, insert a slice of clay cylinder through the threaded section. Tap the tube gently on a forgiving surface (to prevent damage). When the clay nears the top of the cartridge add remaining clay freestyle, forcing your spatula inwards and downwards, continuing to end-tap the tube to eliminate any air pockets.

Hand filling, whilst more cumbersome, does allow you freedom to add colour pigments to Stoneware clay should you wish to experiment with more exotic output.

As you gain more experience, porcelain or grogged (chamotte) clay can be tried but they do need special treatment and may require a different Auger in the extruder. The best clay to start with is Stoneware clay

## 5. Cartridge refilling by Pug Mill

You will require one of our 3.25"/82mm Pugmill Adapters

Add small amounts of water while cycling clay through the pug mill. As little as 1/20 of water by weight is not unusual to achieve the correct consistency. Repeat through the pugmill several times if necessary – you are effectively removing air from the clay and achieving an even consistency similar to a standard throwing clay but slightly wetter.

Fix the Cartridge-Pugmill adapter in place and load tubes directly from the pug mill applying a force which ensures all air pockets are removed.

Do not add too much water to the clay else the internal auger of the pugmill will lose traction against the sides. Add water sparingly and get to know your clay-pugmill-cartridge balance. For best results you should use a De-airing pug mill and a double auger machine will give you better performance than a single auger.

# Understanding Clay

It is important to understand the key physical and chemical processes through which clay transitions during preparation, printing, drying and kiln firing. This knowledge will help you and your students plan clay projects where defects are minimized.  The artistry and science of ceramic materials, knowledge accumulated over thousands of years, is now widely available to help you avoid cracking, breaking, exploding and glaze defects in your 3d objects.

## Important Terms and Concepts:

**Wet clay:** Mixed clay ready to be formed. This is clay in its most elastic state and is very sensitive to water variation.

**Leather-hard:** A stage in the drying process when a clay object can be carefully handled without danger of the shape being deformed, but the clay is still pliable enough so alterations can be made if desired.

**Greenware:** This is the period between formation of your clay object and its drying time before it can be safely bisque-fired.

**Bone dry:** Completely air dry clay. It is very hard but brittle, like a biscuit. It can still be transformed back to wet clay if exposed to water.

**Bisque:** This is an intermediate state achieved after the first kiln firing above 900oC. The vessel is still porous but can no longer be returned to the wet clay phase.  Your piece will still have the ability to absorb water (porosity up to 3% water by weight) but this helps any glaze solution adhere to your object.

## Feldspar and Fluxes

A key component of any clay, feldspars are naturally found and contain various minerals. These include fluxes (e.g. either potassium oxide or sodium oxide, 10-15% by weight),  mixed with alumina ($Al_2O_3$, 17-25%) and silica ($SiO_2$, 60-70%).  So we have the base glass-former, silica, in abundance. But it is crucially aided by the alkali fluxes which lower the maturing temperature of the clay and promote the vitrification process.

**Glaze:**  A glaze is a glass that, on its most basic level, has been assigned to melt at a compatible target temperature. Its silica and flux composition should be matched to your object to achieve comparable thermal expansion (glaze-fit).

In ceramics, glazes contrast with clay bodies in that all particles melt. No particles retain their crystal identity but transition to a hard, vitreous surface.  Glaze contains additions of minerals to lower the melting point of the silica (fluxes like potassium, calcium or boron compounds) and minerals to add different colour (e.g. cobalt, iron and copper oxides) , opacity and finish.

Glazes are applied to bisque-fired ware by painting, dipping or spraying.

**Grog:** A sand-like substance that is added to a clay body to add workability and strength. It is ground from previously fired ceramic substances. It also helps to reduce shrinkage of the clay.

**Maturation not Melting:**  This is the point in the clay firing cycle where there is just enough fusion of the clay particles along with bonding strength for durability - but not so much that melting or deformation of the ware takes place. This point is called the maturing of the clay.

## Shrinkage

Clay shrinks as it dries - both as greenware and then again during the firing processes.

Different clay bodies shrink at different rates. Linear sizes can change as little as 4%, or as much as 15% in TOTAL across a clay's transformative processes.

For example, a typical mid-range stoneware clay (such as that offered in the Claybot Stoneware Cartridge) is specified to shrink 11%. This occurs as 5% during greenware drying, 0.5% during bisque firing (to Cone 06 circa 1000oC ) and the final 5.5% during glaze firing (cone 6, 1225 oC).

And of course, given the variability in natural substances and environmental firing inconsistencies, ±2% on any figure should not be considered unusual.

Depending on your need to have accurately sized finished pieces, be aware that a small change in linear shrinkage percentage can have a significant visual effect. (11% linear translates into 30% volume!) Your designs, therefore, should always account for shrinking that will occur before and after firing. (See 11% Shrinkage example below).

**Silica:** also known as quartz. Silica ($SiO_2$) is the most abundant material in the earth's crust.

It is the basic glass-former which melts and begins to fill air-spaces in the clay structure during a bisque-firing or, forms a glass surface when used as a glaze. By itself, silica melts at 1715°C and would be useless in studio ceramics without fluxes – which lower the melting temperature and allow it to flow as glass in a usable range (1060-1300°C).

**Sintered:** When clay is fired to red heat (c. 900 oC), it becomes sintered – a heat which causes the particles to stick together even before the fluxes and glass-formers begin to interact. Once the

clay is sintered, it can no longer be slaked down and reused.

**Slip:** is a term which has more than one definition in ceramics.

Its principal role is when as a simple mix of water and clay it is used as a glue to attach leather hard or dry elements together (e.g. handles to mugs, spouts to teapots).

Slip is also the term used for a mix of clay and other minerals and fluxes that is applied to dry or leather hard ware to enhance the surface in the glaze firing. Its main objectives are to improve glaze coverage, add certain colour saturations and improve fired hardness.

And finally, it is a term used for the clay slurry when casting into mould shapes. This slip is deflocculated to minimize water content and optimize viscosity.

**Plasticity:** is a term referring to the ability of a clay body to assume a new shape without returning to the old (it being 'elastic' if it springs back).

Plasticity is mainly, but not only, a function of particle size. In addition, the electrolytic character of flat clay particles (they have opposite charges on the faces and edges) is just as important.

Normally clays of finer particle sizes are more plastic because they pack more closely together with electrolytically charged water molecules. But more water means more shrinkage at later stages. The ideal condition, therefore, is to produce a clay body with a variety of particle sizes for good plasticity, both dry and bisque strength, yet without excessive shrinkage. For example, a combination of kaolins, ball clays and bentonite enable bodies of more plasticity with less drying shrinkage and better drying performance than kaolin alone.

Plastic clays enable large, thin pieces to be made. Non-plastic clays are short and prone to water loss at all stages so better for casting but not larger pieces.

Additive minerals such as bentonite and veegum need only be included in very small quantities to achieve large increases in plastic behaviour.

**Vitrification:** As temperature in a clay body continues to climb beyond initial sintering, towards the high-fire range, the fluxes and glass-formers within the body start to form a glassy-phase (rather than crystallization). Vitrification is sintering in the presence of a fully developed glass-phase, where the air spaces between particles are almost completely filled. The filling of these air spaces, along with the closer arrangement of the sintered particles, accounts for firing shrinkage in vitrified wares.

If done correctly, this provides high density, a good degree of impermeability, and strength.

**Wedging:** Over time, effects of mould growth and particle electrical charge creates non-homogeneous stiffness across the clay matrix. Wedging clay is similar to kneading bread dough. It evens out the stiffness and returns it to a consistency found at time of production. It is not uncommon for clay to soften quite dramatically on wedging.

**Air Drying Clay - why it is important to let clay work dry slowly**
Wet clay contains a minimum of 25% water. If clay is drying, water has started to evaporate. As this happens, particles of clay draw closer together resulting in shrinkage. If that occurs at different rates - at the interface between dry and moist clay – then stress cracks become likely. Many problems with clay are formed by uneven rates of drying. Sometimes stress appears immediately as visible cracks or warpage. Sometimes later - as cracks, bloating or explosion during kiln firing. It is so important to ensure drying is even. Uniform thicknesses throughout your pieces aid good drying. And controlled exposure in humid conditions, with the aid of polythene protection, helps well.

Clays which have very fine particle sizes will shrink more than clays with larger particle sizes simply because they have more water to lose. Porcelain clay has very fine particle sizes which, whilst being very plastic, also shrinks the most. However, these bodies once dry, have the most strength in the dry greenware state because their small particles are packed closely together. Clays with grog (large particles) are best for sculpture and shrink the least.

When almost all water between the layers of clay particles have evaporated, your object has reached a leather-hard/bone-dry stage. The particles themselves are still 'damp' (chemically bonded water molecules are still attached) but more drying will not cause any additional shrinkage.

**Accelerated Drying**
If clay objects are just damp or slightly wet, it is not unreasonable to speed-up drying using a fan or warm kiln room. But swings in environmental temperature must remain slow - evaporation of the remaining non-bonded water needs to occur gradually.

## Kiln firing – Key Temperature Points

During the clay firing cycle in a kiln, clay transforms from a totally fragile substance (air-dry clay!) to a stone like substance (ceramic). A typical kiln firing cycle is planned to ‘ramp’ temperature upwards at approximately 150°C per hour. The firing moves through several stages, outlined below.

### +100°C Initial Kiln Drying

Complete drying doesn’t take place until your clay piece is in the kiln and the boiling point of water has been surpassed (100 oC). This must happen slowly, or the formation of steam within the body of the clay may cause it to burst. For this reason, the thermal ramp at the start of the cycle is shallow and the kiln lid opened to allow steam to escape.

### +300°C Burn Off – Carbon, Sulphur and organic impurities

Clay bodies all contain carbon, organic materials, and sulphur which will burn off between 300°C and 800°C (570°F and 1470°F). Note your kiln should be vented to the outside to prevent the danger of breathing the various oxides and sulphate fumes which generate in this period.

### +500°C Chemically Combined Water Driven Off

After the clay is air dried, it still contains about 15% water which is chemically bonded. Clay is chemically defined as a molecule of alumina and two molecules of silica bonded with two molecules of water.

The chemically combined water bonds weaken during the same heating ramp for Carbon and Sulphur burn off (350°C and 800°C). The ceramic will become substantially lighter but there is no physical shrinkage. And it remains critical during this stage to ensure temperature rise is slow to prevent steam pressure build-up which can result in shattering.

This irreversible chemical change is known as dehydration.

### 572°C Quartz Inversion

Quartz, also called silica oxide, has a crystalline structure that changes at a temperature of 572°C (1060°F). This change in crystalline structure (Quartz Inversion) will cause the clay body to increase in size by 2% while heating but will lose this 2% when cooled. The ware is fragile during this change and kiln temperature must be raised and cooled slowly across this temperature point.

### +900°C Sintering / Bisquing

Starting at about 900°C the clay particles begin to fuse. This process is called sintering that when completed, the clay has become ceramic. Once temperature is reached between 1000°C (cone 06) to 1060°C (cone 04) it is bisqued. At this stage, the ceramic is porous, somewhat fragile and not yet vitrified and is called Earthenware or Bisque. The Bisque allows wet, raw glazes to adhere to the pottery before Glaze firing.

### +1000°C Vitrification and Maturity

Vitrification is the progressive fusion of a clay that makes the finished product harder and more durable. As vitrification proceeds with temperature increase, the proportion of glassy bond increases and the porosity of the fired ceramic becomes lower as the air cavities fill in with glass.

It is also during this stage that mullite or aluminium silicate crystals are formed that act as a binder, strengthening the clay body even further.

Bisque firing alone does not make clay bodies impermeable to water in most cases. However, Porcelain, which is among the most vitrified ceramic, is impermeable even without glaze. Stoneware is semi-vitrified and would not be impermeable without glaze.

### 220°C Cooling

The crystalline form of silica, as it cools past 420°F (220°C) must be cooled slowly as it moves through this critical temperature to avoid cracks. This is the final phase of your thermal 'RAMP'.

## Glaze Firing

When your piece is back in the kiln and put through a glaze firing cycle, it will undergo similar processes to the bisque fire but to a different heat ramp profile: impurity gases are expelled, sintering of the glaze particles take place above 800°C and at just above 1000°C (cone 06) needlelike mullite (aluminum silicate) crystals begin to form an interlocking structure. This glassy phase creates a combination of dense vitrification, great body strength, and a reinforced clay– glaze interface, all of which we want in high-fired functional ceramics. This is where glaze fit is crucial i.e. when the shrinkage characteristics of the glaze matches that of the clay vessel.

Around 1060-1240°C (cone 4-7) free silica in the clay and glazes that have not combined with fluxes to form a glass, begin to transform into cristobalite (crystalline quartz). This is an irreversible change. Note: Do not heat soak your piece above this temperature range because it creates pieces with low thermal shock resistance.

As your glaze-fired piece cools the molten glaze passes from liquid to thermoplastic to solid. Throughout this process of annealing, the physical volume of the glaze and body change constantly, and rarely at the same rate. This is due not only to differing thermal expansion of the various materials, but also to the inversions of quartz (572°C) and cristobalite (260°C).

Whilst cooling stresses through these stages are usually dissipated in all glass and ceramics without issue, there is a critical zone where cooling must be slow in order to accommodate differential shrinkage. For most glazes the critical zone extends from around 540°C down to 340°C, below the quartz inversion temperature. But note a porcelain glaze anneals at a temperature above quartz inversion and cooling ramps should be adjusted accordingly.

# Additional Training

## CLAYBOT TRAINING : ON-SITE & VIDEOS

**Installation Day:**

We will personally deliver your Claybot anywhere in the UK and combine that with a brief workshop.

After assembling and calibrating the printer, we will show you how to prepare, run and fine tune the printer for different shapes . If necessary we also give a short introduction on how to design and prepare your 3d object files for successful prints.

**Individual or Cluster Workshop:**

We bring a demo printer, set it up in your preferred location and show you how to run and fine-tune the printer for different shapes. Where requested we will also give you a short introduction on how to approach your 3d-modelling and prepare your file into GCode for printing by Claybot.

Price on application – depending on location but guideline price is £350.

**Overseas Deliveries & Support:**

Claybot is an out-of-the-box product save a few bolts and some initial checks and calibration tests. We can ship anywhere in the world once we have the voltage/current specifications of your local electricity supply.

We can travel to supply workshops and/or training but we would recommend that face-time video webinars can offer a whole lot in terms of advice and expertise about printing possibilities and potential pitfalls. Of course, this also reduces costs significantly.

To find out more about our face-time technical webinars please contact: robby@claybot.co.uk

Alternatively, our set-up and maintenance videos offer some insight into how your Claybot should be operated and looked after.

# NOTES

# NOTES