Lab-on-a-chip workshop activities for secondary school students

Mohammad M. N. Esfahani,[1,2] Mark D. Tarn,[1] Tahmina A. Choudhury,[1] Laura C. Hewitt,[1] Ashley J. Mayo,[1] Theodore A. Rubin,[1] Mathew R. Waller,[1] Martin G. Christensen,[1] Amy Dawson,[3] Nicole Pamme[1]

[1]*Department of Chemistry, University of Hull, Cottingham Road, Hull, HU6 7RX, UK*

[2]*School of Engineering, University of Hull, Cottingham Road, Hull, HU6 7RX, UK*

[3]*School of Biological, Biomedical and Environmental Sciences, University of Hull, Cottingham Road, Hull, HU6 7RX, UK*

The ability to engage and inspire younger generations in novel areas of science is important for bringing new researchers into a burgeoning field, such as lab-on-a-chip. We recently held a lab-on-a-chip workshop for secondary school students, for which we developed a number of hands-on activities that explained various aspects of microfluidic technology, including fabrication (milling, moulding, and wax printing of microfluidic paper-based analytical devices, μPADs), flow regimes (gradient formation via diffusive mixing), and applications (tissue analysis and μPADs). Questionnaires completed by the students indicated that they found the workshop both interesting and informative, with all activities proving successful, while providing feedback that could be incorporated into later iterations of the event.

I. INTRODUCTION

Lab-on-a-chip is a powerful technology with huge potential for impacting diagnostics, chemistry, and biology,[1-4] but even after developing to a great extent over the last quarter of a century[5-14] and with commercialisation starting to really take off,[15-18] the general public is still largely unaware of it. Many universities and institutes hold showcase events intended to instruct the public on the research being undertaken and its real-world application, and more-and-more frequently these events are being extended to incorporate activities for schoolchildren. Introducing schoolchildren to new areas of science beyond their curriculum is important in engaging and inspiring potential future researchers in exciting fields. However, this is easier said than done, since many aspects of science require a certain level of background knowledge and, while exciting to the researchers in a field, can sometimes be a "dry" subject when explaining to a wider audience. Thus, the challenge when discussing novel fields to children is to keep the main points simple, relevant, and as far as possible, jargon-free, while making them exciting and fun. This is best achieved by preparing hands-on activities that allows schoolchildren to experience a scientific concept in a fun way whilst being intuitively instructed in its fundamentals.

A literature search shows that a number of hands-on activities have been developed over the last decade or so to introduce scientific concepts to schoolchildren, undergraduate students and the general public, dealing with the fabrication, operation and application of microfluidic devices.

Activities dealing with fabrication have been developed, for example, by Yang et al.,[19] who prepared inexpensive moulds of wooden coffee stirrers to form Jell-O chips as an analogy of soft lithography fabrication of polydimethylsiloxane (PDMS) devices.[20, 21] Other groups have since utilised this methodology for their own educational experiments,[22, 23] while Jimenez and Bridle[24] formed channels out of FIMO® soft polymer clay by moulding it around wooden structures. Nguyen et al.[25] developed their shrink-film based microfluidic production technique[26] for educational purposes to form a mould for PDMS, and this has been used by several groups.[27, 28] DeVore et al.[29] and Berkowski et al.[30] developed photolithography experiments for students using positive and negative photoresists, respectively. Yuen and Goral[31] demonstrated a low cost glass fabrication technique for university students that utilised a low-cost glass-etching cream available from stores.

A variety of hands-on microfluidic experiments have been demonstrated for educational purposes at various levels, employing conventional microfluidic devices or platforms fabricated via the above methodologies. Experiments have included laminar flow and diffusive mixing,[19, 27, 32-35] gradient formation,[28, 36, 37] droplet generation,[23] pH sensing,[28, 33, 35, 38] particle separation,[24, 39] capillary electrophoresis,[34, 40-42] crystal precipitation,[33] particle synthesis,[27] chemical synthesis,[27] water electrolysis,[22] enzyme linked immunosorbent assays (ELISA),[43] and the modular construction of microfluidic setups and instrumentation (using LabSmith Inc. products).[44]

Paper microfluidics[45-47] are also proving popular for educational demonstrations and experiments due to the ease and speed of fabrication, and the simplicity of experiments that can be performed. Devices have been fabricated by melting wax designs onto filter paper,[48] punching leaf-shaped devices out of chromatography paper,[49] using a PMMA (polymethyl methacrylate) stencil to draw designs onto filter paper,[50] and by melting parafilm designs into tissue paper.[51] Such paper microfluidic devices have been used to perform colourimetric assays of simple analytes in a range of common samples,[48, 50, 51] and to simulate forensic analysis of a mock crime scene.[49]

Recent examples of introducing microfluidic concepts to students have involved preparing apparatus and activities that often do not use microfluidic channels themselves, but rather simple and fun exercises demonstrating the core principles. For example, Drazer and Frechette[2, 52, 53] developed a working analogy of the Deterministic Lateral Displacement (DLD) particle separation method[54, 55] using a pillar array fabricated out of Lego®. Heriot-Watt University (UK) has prepared several workshop events and activities for introducing microfluidic concepts to

school children.[24, 35] In one instance, the group prepared three workstations with microfluidic devices that instructed students on (1) laminar flow, (2) mixing, and (3) DNA analysis using pH sensing as an analogue.[35] Jimenez and Bridle[24] from the same group reported a number of hands-on exercises for introducing the detection of waterborne pathogens[56, 57] to schoolchildren. Each stage of pathogen analysis was shown in an entertaining way, making good use of FIMO® soft polymer clay to fabricate microfluidic channels and to demonstrate immunomagnetic separation (IMS). For the IMS activity, clay was moulded around magnets that allowed their separation from non-magnetic clay spheres, and this was shown in both an oversized Petri dish and an oversized microfluidic chip. Fluorescent FIMO® spheres were also used to mimic fluorescence microscopy. In addition, the group demonstrated a Lego® DLD array based on the aforementioned work.[2, 52, 53]

The University of Hull has been showcasing its research to the general public for several years. However, for the Hull Science Festival 2015 (#HullSciFest), held in March 2015,[58] the microfluidics group at the University of Hull developed a one-hour workshop for secondary school children (aged 13-14) with the purpose of instructing them in the design, fabrication, operation, and application of lab-on-a-chip technology in a fun and interesting way that incorporated a variety of hands-on activities. In particular, the activities were intended to not only teach the students about lab-on-a-chip in general, but to highlight the microfluidic fabrication facilities at the University and the related research activities being performed. However, many of these processes have not been covered in the previous literature, while most of the reported educational experiments are aimed at a higher level than secondary school students or required setup and execution timeframes that could not be achieved in a one-hour workshop. Thus, a number of new hands-on activities had to be developed for the lab-on-a-chip workshop that were simple, exciting, informative, relatable to actual scientific concepts/techniques, and hands-on, while being short enough (10-15 min each) to allow multiple activities to be performed in one hour.

The teaching outcomes of this exercise were actually two-fold, as a group of undergraduate project students were tasked with developing the activities, under the supervision of PhD students and PostDocs, as part of a group project titled "Explaining Lab-on-a-Chip to the Public". Five workstation activities were developed that explained lab-on-a-chip using a mixture of analogous exercises and oversized devices that the schoolchildren could operate (Fig. 1). These activities taught the students about (i) the manufacture and prototyping of microfluidic device by CNC milling, demonstrated via the analogous use of a pantograph sketching apparatus, (ii) polymer injection moulding via the use of chocolate moulding in silicone, (iii) paper microfluidics using wax crayon designs on filter paper, (iv) gradient formation using an oversized gradient chip, and (v) on-chip tissue studies using an oversized device.

II. MATERIALS AND SETUP

A. Chemicals

Yellow food dye powder (Tartrazine), blue food dye powder (Erioglaucine disodium salt), and red food dye powder (Erythrosin B) were purchased from Sigma-Aldrich (Dorset, UK) and prepared in purified water, then passed through 0.22 μm syringe filters. pH indicator paper (Whatman) was purchased from VWR (UK). Filter paper discs (110 mm diameter, grade 390, Sartorius Stedim Biotech) were purchased from Scientific Laboratory Supplies (Nottingham, UK). Milk chocolate bars, fruit juices, lemon juice (as a source of citric acid), and wax crayons were purchased from local supermarkets. Paramount crystals (partially hydrogenated palm kernel oil combined with soy lecithin and citric acid) used for working with the chocolate were ordered from The Cake Decorating Co. (Nottingham, UK). Smooth-On SORTA-Clear 18 Translucent Silicone Mold Rubber, used for preparation of silicone moulds, was purchased from Bentley Advanced Materials (Worcestershire, UK).

B. CNC milling: *Pantograph*

"Baker Ross Scratch Art Doodle Sheets", featuring a rainbow coloured sheet coated with a layer of black wax, and a "John Adams Sketch-a-Graph" pantograph were purchased from Amazon (UK). The scratch art sheets were cut to rectangular pieces of 10.5 cm x 7 cm. The pantograph was mounted to a square piece of board via one of its arms, allowing movement from a fixed point. A piece of steel rod (~250 g) was machined using a CNC milling machine and placed over a blunted graphite nib/needle in order to weight the nib down. The weighted nib setup was fixed to the end of a free arm of the pantograph for scratching designs into the scratch art sheets. Extra weight and stabilisation had to be added to the middle of that same arm, and so another aluminium cylinder was milled that was fixed underneath the arm to add support to the pantograph structure. A plastic stylus was fixed into the end of another pantograph arm, which was used to trace the designs from a reference image. An A4 size sheet featuring four common microfluidic chip designs (see Fig. S1 in the supplemental material)[59] was printed, laminated, and taped to the board such that the chip designs were positioned beneath the plastic stylus, while a scratch art card was positioned and taped down beneath the weighted nib. The designs included: (i) a serpentine channel, (ii) a Y-shaped channel, (iii) four straight, parallel channels, and (iv) a gradient channel design.

C. Injection moulding: *Chocolate chips*

Keyrings, fabricated in PMMA polymer and featuring the letters "LOC" (Lab-On-Chip) and a serpentine microchannel design, were manufactured in bulk to give away to students and the general public at the Hull Science Festival 2015. These were prepared by first designing a mould in SolidWorks (Dassault Systèmes SolidWorks Corp., France) and creating a G-code for the design in SolidCAM (SolidCAM UK, Barnsley, UK). The G-code was transferred to a CNC milling machine (Datron M7, Datron, Germany), and the design of the keyring mould was

milled out of aluminium. The aluminium mould was fixed into an injection moulding machine (Babyplast 6/10P, Rambaldi+Co, Molteno, Italy) (Fig. 2a), and used to produce the keyrings (5.5 cm long x 2.5 cm wide x 0.2 cm thick) from PMMA granules (Sabic, Middlesborough, UK) (Fig. 2b).

Silicone moulds were prepared by placing the PMMA keyrings into the compartments of accessory boxes that featured adjustable plastic dividers. Each compartment had dimensions of 6.5 cm x 3.5 cm, and there were a total of 18 compartments into which keyrings (minus the actual rings) were fixed using double-sided tape. SORTA-Clear 18 is a silicone moulding rubber that is certified as being safe for food contact, and came in two parts (Part A and Part B). 80 g of Part A was added with 6.5 g of Part B and mixed thoroughly for at least 3 min, before being placed in a vacuum desiccator. The vacuum was slowly increased to 0.9 MPa and held at that pressure for 10 min, before being slowly decreased. The silicone rubber mixture was poured over the keyrings in each compartment of the accessory boxes and left to set for 24 hours. Once set, the cured silicone pieces were removed from the compartments to yield the final chocolate moulds (Fig. 2c).

Molten chocolate was prepared using an improvised bain-marie water bath comprising a saucepan of water on a hot plate, with a mixing bowl placed in the pan. 100 g of milk chocolate, broken into pieces, and 4 g of paramount crystals was added to the mixing bowl, then melted by boiling the water in the bain-marie and mixed with a spoon. The paramount crystals allowed the chocolate to be thinned to the point that the mixture could easily be drawn into and pushed out of a 10 mL disposable syringe (BD Plastipak, VWR). A coolbox was located nearby for rapid cooling of the molten chocolate when required.

D. Paper-based analytical devices: *Wax on filter paper*

Paper microfluidic devices were prepared by drawing channel designs with wax crayons onto discs of filter paper (Sartorius), similar to the method of Cai et al.,[48] then placing the discs onto a hot plate for 30 seconds in order to melt the wax into the paper, rather than placing them in an oven. The process could also be sped up by placing a metal block on top of the paper on the hot plate. Three main designs were employed for the workshop demonstration: (1) a Y-shaped channel for showing diffusion of two coloured liquids (Fig. 3a), (2) a gradient channel for demonstrating the ability to generate multiple shades of colour from only two starting coloured liquids (Fig. 3b), and (3) a straight channel with a bulb that was used to demonstrate laminar flow assays (Fig. 3c). The straight channel chip was further prepared by fixing a rectangular strip of universal pH indicator paper with sellotape on to the back of the filter paper, such that it crossed the straight channel. A rectangular strip of filter paper was cut out from a separate filter disc and immersed in a solution of blue food dye (Erioglaucine disodium salt),

then removed and allowed to dry before also being sellotaped across the straight channel between the pH paper and the bulb part of the design. The designs on each paper device were simply dawn by hand with wax crayons, since the nature of the experiments did not require accurate fabrication, and about 30-50 devices of each design were prepared for the workshop.

The workstation for the paper devices was set up such that each student had vials of yellow food dye (Tartrazine) and blue food dye (Erioglaucine disodium salt) in water. Some students were given vials of water, while others were given vials of lemon juice. Each student was also given a few plastic Pasteur pipettes, some wax crayons, a few filter paper discs, and blue roll (Kimwipe) on which experiments were performed to soak up any spilled liquids. The hot plate was set up at the workstation to ensure freshly drawn wax designs could be melted into the paper.

E. Gradient formation by diffusive mixing: *Oversized gradient microfluidic chips*

Gradient mixing devices were designed in SolidWorks based on upscaled versions of microfluidic devices used in the literature.[60-63] Two devices were prepared, each featuring two inlet channels that would repeatedly split, mix, and recombine the fluid streams over several levels of branching channels and serpentine mixing channel structures. The designs were converted to G-code via SolidCAM and milled into 6 mm thick sheets of polymethylmethacrylate (PMMA) polymer using a CNC milling machine (Datron M7). Design 1 (the "demo chip") featured four levels of branching/serpentine channels that resulted in six outlet channels, and was milled into a 30 cm x 21 cm polymer sheet (Fig. 4a). The channels were 1 mm wide and 300 μm deep, with holes milled into the inlet and outlet channels. Design 2 (the "juice chip") consisted of two levels of branching, yielding four outlets that opened into reservoirs, that was milled into a 14 cm x 10 cm polymer sheet (Fig. 4b). These channels were 1 mm wide and 1 mm deep. The milled chips were bonded to bottom sheets of 6 mm thick PMMA using double-sided tape to yield the final devices.

Plastic pipette tips (100 μL) were cut to size and glued, using Araldite Rapid or Araldite 2014 epoxy resins (RS Components, Northants, UK), into the inlet holes of designs 1 and 2, and into the outlet holes of design 1. Design 1 was set up to be constantly running during the workshop in order to show students the chip in operation. PTFE tubing (0.3 mm ID, 1.58 mm OD, Supelco, Dorset, UK) was glued into the pipette tips in the two inlet holes of design 1, and attached at its other end to two 10 mL disposable syringes (BD Plastipak) via syringe adapters (Upchurch). The syringes contained aqueous solutions of blue food dye (Erioglaucine disodium salt) and red food dye (Erythrosin B), respectively, and were placed on a syringe pump (PHD 22/2000, Harvard Apparatus, UK). The dye solutions were continuously pumped through the chip at a flow rate of 20 μL/min.

Design 2 was set up to be operated by hand by the students during the workshop. This was achieved by attaching 10 mL disposable syringes filled with fruit juices (e.g. cranberry juice, blackcurrent juice, orange juice, pineapple juice), respectively, to the cut-down pipette tips in the inlet holes of the device.

F. Tissue-on-a-chip: *Oversized tissue chip*

Microfluidic devices for performing investigations on tissue biopsies have been used for several years at the University of Hull.[64] Here the chips feature a microfluidic channel that passes through a tissue chamber; a lidded compartment that allows placement of the tissue in the flow path such that media and reagents can be pumped over the tissue. For the workshop, an oversized tissue chip was fabricated that incorporated these basic concepts. The chip design (Fig. 5) were prepared in SolidWorks and transferred to a CNC milling machine (Datron M7) via a G-code prepared in SolidCAM. A single flow channel, with a length of 11 cm and a width of 3 mm, was milled to a depth of 6 mm in a 15 cm x 15 cm sheet of 12 mm thick PMMA polymer. Three access holes were milled into a second sheet of 150 cm x 150 cm x 12 mm PMMA: a 3.5 mm diameter inlet hole, a 3.5 mm diameter outlet hole, and a 20 mm diameter hole in the centre of the sheet that would act as the "tissue chamber". Double-sided tape was applied to the plate that featured the channel design, and the section of tape covering the channel was cut away with a scalpel. This channel plate was then bonded to the access hole plate via the double-sided tape.

A "tissue" chamber was prepared by taking a 50 mL centrifuge tube (VWR, UK) with a screw-on lid, and cutting it to a length of 4 cm from the top. The section featuring the lid was glued onto the central chamber (20 mm diameter) of the access hole plate using Araldite Rapid epoxy resin. PTFE tubing (0.3 mm ID, 1.58 mm OD) was glued into the inlet and outlet holes, and was set up to introduce solutions by negative pressure. The outlet tubing was connected to a 20 mL disposable syringe (BD Plastipak), while the inlet tubing was fed into a plastic beaker containing either water or lemon juice. Books of universal pH indicator paper were also placed at the workstation.

III. HAZARDS

Full risk assessments were carried out for each of the workstation activities. Efforts were made to ensure that experiments could be performed using standard household items, for example using lemon juice as a source of citric acid, the use of fruit juices and solutions of food dyes as sources of coloured liquids, and food-grade silicone for the preparation of the chocolate moulds. Care was taken that students did not touch the hot plates employed for melting wax during the preparation of paper microfluidic devices, and for melting the chocolate used for the moulding of chocolate microfluidic chips.

IV. WORKSHOP PROCEDURES

The Hull Science Festival 2015 Lab-on-a-Chip Workshop was held for three groups of students (aged 13-14) from different schools, with the workshop taking one hour for each school group. The purpose was to introduce lab-on-a-chip technology to school students, whilst demonstrating some of the types of microfluidic chip fabrication and research that takes place at the University of Hull. The workshop took place in a large room, with one table set up per workstation throughout the room and each station manned by the undergraduate student (demonstrator) who had developed the activity for it. When a group of students entered the room, they were given an initial introductory talk by the Professor, who supervised the overall running of the workshop, which briefly described what lab-on-a-chip is and why it is useful, before discussing the purpose of the workshop and general safety concerns. The larger cohort was then split into smaller groups of 4-5 students and each group directed to a workstation.

There, the students were given a short talk by the demonstrator about that station, with a description of the technique that was being demonstrated and how it was related to the use of microfluidics in a research setting. They would then be instructed in how to perform the workstation activity, and each student was given an opportunity to undertake every one. Posters (A4 size) were designed by the undergraduate student demonstrators (Figs. S1-S6 in the supplemental material),[59] and were placed at each workstation to describe the activity. However, given the time limitations and the fact that many aspects of the field would be completely new to the students, the introductions and explanations were kept short and simple, describing only the core aspects of each technique without going into too much detail. A workshop ran for one hour, with each workstation running for approximately 10-15 min, after which the student groups would be directed to a new workstation. During the final workstation activity of each session, the students were given a questionnaire to fill in (see the supplemental material)[59] in order to determine their thoughts on the workshop in general, each individual activity, and how the workshop had affected their knowledge of lab-on-a-chip technology. The following sections describe the purpose of each workstation and how it was described to the students, in addition to how each activity was performed by the students.

A. CNC Milling: *Pantograph*

Micromilling is a powerful fabrication technique that can be used to manufacture microfluidic devices, particularly for rapid prototyping, although it is a relatively underused technique in microfluidic research presumably due to relatively high start-up costs, required lab space, and expertise. A recent review by Guckenberger et al.[65] gives an excellent overview of protocols and considerations for the micromilling of microfluidic devices. Here, chip designs are prepared in CAD (computer aided design) software and transferred to a CNC (computer numerical controlled) milling machine, which uses a cutting tool to cut the design out of a substrate. CNC

micromilling is employed at the University of Hull for the direct milling of microfluidic designs into glass and polymer, and for the milling of masters out of metals (e.g. aluminium) for the microinjection moulding of polymer chips.

Since CNC micromilling involves the cutting of channels into a substrate, the activity for this workstation was intended to mimic this process using a pantograph. By modifying the pantograph to include a weighted nib/needle, channel designs could be traced from a poster (Fig. S1 in the supplemental material)[59] into scratch art cards, with the nib cutting away a layer of black wax from the card as it was moved to reveal the coloured design beneath. The background of micromilling for microfluidic chip fabrication and its relation to the pantograph activity was explained to the students by the demonstrator with reference to the poster (Fig. S2 in the supplemental material).[59] Specifically, the students were informed of the following: (1) the key components and principles of a CNC milling machine, by which a computer controls a cutting tool to precision cut an uploaded design drawing out of a workpiece; (2) that milling can be used to cut microfluidic channels directly out of a material (e.g. plastic or glass) for device fabrication, or alternatively can be used to cut a design out of metal for use as a master in injection moulding of microfluidic devices (with suitable reference made to the chocolate moulding workstation); (3) the pantograph setup, and how its components can be related to CNC micromilling. In particular, students were informed that the channel template on the poster represented the CAD drawing on a computer, the stylus and arms of the pantograph demonstrated the transfer of the design to the cutting tool (via computer aided manufacturing, CAM, software), the weighted nib imitated the spindle and cutting tool, and the scratch art card served as the workpiece (Fig. 6a). (4) The operation of the pantograph, by which students would trace designs from the template while the nib cut the design into a scratch card. It should be noted, however, that the focus of the activity and application was based on only two of the core components of CNC milling: (i) the transfer of a design from a drawing to a physical workpiece, and (ii) the cutting of that design into the substrate via a moving arm and a cutting tool. Hence, the actual computer numerical control part of the procedure was not explained in any great detail beyond the fact that the cutting arm is precision controlled by a computer based on the design.

The students selected a microchannel design from the template sheet (Fig. S1 in the supplemental material),[59] and the demonstrator fixed the template design and scratch art card to the pantograph board such that the stylus of the pantograph was placed on the template while the weighted nib was located on the scratch art card (Fig. 6b). The students then slowly and carefully traced the template design in order to ensure that the weighted nib was stable enough to cut into the black wax in a steady manner; moving the stylus too fast would result in poor transfer of

some of the lines being cut into the scratch art card. Upon finishing, the students were then given a metal stylus so that they could cut their name into the wax on their scratch art card, and took their finished cards home with them.

Fig. 6c shows examples of the channel designs cut into scratch art cards compared to the template designs on the poster, showing a good transfer of each design via the pantograph. Furthermore, two sets of scratch art cards were used: some that were thick and rigid and others that were thin and a little more flimsy. It was determined that it was easier to transfer designs into the thicker cards, while the channel lines did not always come out very well in the thinner cards. On the whole, the students were able to recognise the association between the pantograph "etching" and the CNC milling of microfluidic devices, and this is shown by the results of the questionnaire that are described later. On the whole, the students responded positively to the activity, with one writing in their feedback that it was "*Explanatory but enjoyable, creative, fun and a lot more hands on*" compared to some other stations.

B. Injection moulding: *Chocolate chips*

Injection moulding is an extremely popular mass production technique that involves the fabrication of a mould into which molten polymer is injected under high pressure, filling the mould and forming the final product upon cooling and release of the polymer. Microinjection moulding for the fabrication of microfluidic devices has thus also proven successful since a larger number of almost identical devices can be produced in a short time using a mould,[66-70] and has been used extensively for the production of PMMA, PC (polycarbonate), COC (cyclic olefin copolymer), and COP (cyclic olefin polymer) microfluidic chips at the University of Hull. In order to demonstrate this process to school students, an activity was set up to introduce molten chocolate into a mould, which would then be allowed to cool to provide a chocolate microfluidic chip.

As described in section 2.3, food-safe silicone moulds were prepared from PMMA keyrings (Figs. 2b,c) that had been themselves injection moulded as give-away items at the Hull Science Festival for several years. The silicone moulds featured a microfluidic channel design and the letters "LOC" (Lab-On-Chip). Prior to the school groups starting the workshop, the demonstrator of the workstation set up an improvised bain-marie to melt a bowl of chocolate (mixed with paramount crystals to decrease the viscosity of the chocolate), such that the chocolate would be kept molten throughout the course of the hour. Once a group of students had been taken to the workstation, the demonstrator gave an introductory talk regarding the technique of polymer injection moulding for microfluidic device fabrication and the relation of the chocolate moulding method to it, with the help of a poster showing both a typical injection moulding setup and the chocolate moulding activity (Fig. S3 in the supplemental material).[59] Specifically, the demonstrator discussed the following: (1) the operation of a polymer injection moulder, as

described above, with reference to the major components of such a machine (i.e. a hopper containing granules of plastic, a mould tool (master), and a heated barrel and screw that melts the polymer granules and forces them into the mould tool. (2) The use of injection moulding for the fabrication of polymer microfluidic devices based on a design that had been milled into the metal mould, with reference to the pantograph workshop activity (as an analogy of micromilling) and to the PMMA keyrings that had themselves been injection moulded. The keyrings were shown to the students both as examples of moulded polymer chips, and to highlight the fact that these keyrings had themselves been used as masters for the food-grade silicone moulds that the students would be using here. (3) An explanation of the chocolate workstation activity and its relation to polymer injection moulding, in which the silicone moulds said to represent an aluminium master, the chocolate pieces the polymer granules, the bain-marie the heated barrel and the nozzle of the injection moulder for melting the chocolate/polymer, and a 10 mL disposable syringe the barrel/screw of the machine.

The students were then invited to take the 10 mL disposable syringe and draw 4 mL of the molten chocolate into it (Fig. 7a), before carefully filling a silicone mould with the chocolate (Fig. 7b). 4 mL had been found to provide enough material for the mould with room for some error and spillage. After a few minutes, the moulds containing the chocolate were wrapped in aluminium foil and labelled, then placed in the coolbox in order to try to rapidly cool them to solid form, with a view to handing the final chocolate chips (Fig. 7c) back to the students at the end of the workshop session. However, due to students performing the activity one group after another, many of the chocolate chips were not fully set before the end of the workshop. This issue had actually been anticipated, and so the demonstrator had prepared a batch of chocolate chips the previous day in order to ensure that each student received a chip. Prior tests with the chocolate chips had demonstrated that, for the given amount and thickness of chocolate in the mould, it took less than 10 min to solidify the chips in a conventional fridge (~4 °C), hence it could be feasible in future to provide all students with their own chocolate chips with a suitable cooling unit.

This workstation, perhaps unsurprisingly, proved to be the most popular of the activities, with the students enjoying both the activity itself but also the fact that they received a chocolate treat at the end. In the feedback provided, many students called it "*interesting*" and "*well explained*", with one comment stating that "*The chocolate station was my favourite because the explanation was good and it was really fun, also I think I learned a lot from it*". An interesting problem experienced with the activity, however, involved trying to discourage students from eating the molten chocolate directly from the syringes.

As a side note, while the silicone moulds and chocolate chips were used here as an analogue for microinjection moulding, the method and explanation could easily be repurposed to describe the moulding of PDMS devices. Here, the silicone moulds would represent an SU-8 master, while the chocolate would represent PDMS.

C. Paper-based analytical devices: *Wax on filter paper*

Modern microfluidic paper-based analytical devices (μPADs) were introduced in 2007 by the group of Whitesides.[47] By patterning hydrophobic channel structures on hydrophilic paper, aqueous solutions are able to wick through the porous paper structure while being directed by the hydrophobic barriers.[4, 45, 46, 71-74] Such channels can be prepared via a number of techniques including photolithography, screen printing, laser cutting, plasma treatment, inkjet printing, and wax printing. Detection zones can be formed at desired locations on a paper microfluidic by spotting reagents onto the paper, and upon addition of a sample (e.g. blood, serum, urine, tears, saliva) to the μPAD the presence of different analytes in the sample can be determined at different detection zones. Colourimetric assays have proven the most popular detection method, particularly in combination with smartphone cameras or scanners for image collection and later analysis, although other detection techniques such as chemiluminescence, fluorescence, and electrochemical sensing. The low cost and ease of fabrication of μPADs has made them very popular for developing point-of-care (POC) diagnostic devices in rural and developing areas.[46, 72]

In recent years, the University of Hull has begun investigating the fabrication and operation of μPADs for diagnostics,[75] hence we wished to introduce the school students to this exciting field. Wax printing has proven a popular method of fabricating μPADs,[76, 77] since it requires only that a design is first printed in wax using a conventional wax printer. This process deposits the wax onto the surface of the paper, which is then placed on a hot plate to melt the wax into the thickness of the paper, thus forming the hydrophobic barriers. This process was easily adapted for a workstation activity using conventional filter paper discs and wax crayons. By drawing a design directly onto the filter paper with a wax crayon and melting the wax into the paper on a hot plate, channel structures can easily and rapidly formed that allow aqueous solutions to be directed along desired paths (Fig. 8a).

Multiple paper devices featuring three designs (Fig. 3) were prepared for the workshop activity. When the students sat down at the workstation the demonstrator explained, with the help of a poster (Fig. S4 in the supplemental material)[59] and the pre-prepared paper devices, the following: (1) the fact that water can travel through the pores between the fibres of paper; (2) that by introducing hydrophobic walls or borders, explicitly stated as being walls that water "does not like", such as borders made from wax, channel structures can be drawn on paper that will control where water is able to move; (3) how this concept can be used to form paper-based microfluidic

devices, μPADs, by employing wall designs that allow different liquids to be brought together. The students were also told of how "detection" chemicals can be added and dried onto the paper, and when a sample is added the chemical will change colour, indicating the presence of a certain species, for example a disease or pollutant. At this point, the use of μPADs as low-cost, portable, point-of-care, disposable devices for the testing of diseases, particularly in poorer regions, was highlighted. (4) The concept of laminar flow assays was explained using the pre-prepared chip design that featured a straight channel, a bulb, and strips of pH paper (acting as a detection zone) and blue paper (acting as a control zone) taped across the channel on the underneath of the device (Fig. 3c). In particular, the layout and operation of this chip could be described in relation to what is probably the most widely known laminar flow assay: the pregnancy test, although given the age range of the students, not all of them may have been aware of the principle of the test prior to this, but it is nonetheless the most relatable test for the general populace. (5) Taking these makeshift laminar flow assay paper devices, each student was invited to add a few drops of clear solution to the narrow end (i.e. not the bulb) of the channel via a plastic Pasteur pipette. Unbeknownst to the students, the clear solution contained either water or lemon juice. Some care had to be taken that too much solution was not added such that it was able to cross over the wax barrier, and it helped to have the device tilted just slightly so that gravity helped to direct the liquid through the channel. As the solution passed through the channel, it crossed the pH paper and blue paper before finishing in the bulb, with the wetting of the filter paper allowing visualisation of the pH and blue paper underneath (Fig. 8b). If a student's solution contained only water, the pH paper turned green, while if the solution was lemon juice then the pH paper turned red, indicating "positive" and "negative" results, respectively. The blue paper remained blue, and was explained as being a control channel that demonstrated that the device was working properly.

Following this first test, the students were given devices that featured either the Y-shaped channel design (Fig. 3a) or the gradient mixing channel design (Fig. 3b). Using plastic Pasteur pipettes, they simultaneously added aqueous solutions of yellow and blue food dyes to the two inlets in each device, and observed the behaviour of the fluids as they passed through the channels. Again, it was found that tilting the paper devices downwards slightly helped to direct the fluid flow through the channel structure thanks to gravity. If performed correctly, the Y-shaped channel demonstrated how the yellow and blue dyes mixed in the straight channel to form a green colour (Fig. 8c). While the gradient design was more difficult to get right, it was arguably more rewarding as the two colours were split, mixed and recombined twice to yield four outlets with a gradient of colour going from pure yellow, through different shades of green, to pure blue (Fig. 8d). Due to the speed and ease of operation of the activity, combined

with the fact that multiple devices been pre-prepared, students were invited to have extra attempts if they were not successful the first time.

Finally, students were given blank filter paper discs and wax crayons and asked to draw a design of their choice (Fig. 8e), which ranged from basic shapes, letters, their own names, animals (especially horses), somewhat abstract pieces, and figures from pop culture (the video game character, Pac-Man, proved particularly popular). The paper discs were collected from the students as they finished their drawings and were placed on a hot plate for a minute to melt the wax into the paper, after which they were returned to the students. The students were then allowed to pipette coloured food dye solutions onto their designs, with the wax containing liquids to defined locations that enabled the students to colour different parts of the paper as they wished. The coloured paper discs were then either allowed to dry on the desk or on the hot plate, and given back to the student to take home with them.

The students enjoyed the workshop activity, and while they found the initial tests interesting, they were particularly excited to draw their own designs and decorate them as they desired.

D. Gradient formation by diffusive mixing: *Oversized gradient microfluidic chips*

Microfluidic devices relying on the repeated splitting, mixing, and recombination of two or more reagent streams to form a gradient of the reagents were introduced in the early 2000s by the group of Whitesides.[60, 61] Since then, the use of gradient chips has been successful for a number of biological applications,[78-82] in particular the ability to simultaneously expose a population of cells to a gradient of stimuli concentration (e.g. reagents, drugs) across a chamber (or in multiple chambers) in order to determine the effect of from high-to-low concentrations. At the University of Hull, this has previously been employed to study the effect of different concentrations of a genotoxic chemical on magnetically functionalised yeast cells.[63] Therefore, we intended to create an activity that demonstrated several aspects of gradient production, and flow regimes in general, in microfluidic channels.

As described in the section 2.5, two oversized gradient devices were prepared. The larger of the two (design 1, the "demo chip") was connected to a syringe pump that continuously introduced red and blue food dye solutions into the device over the course of the day, demonstrating a stable flow regime and gradient to the students (Fig. 9a,b). With direct reference to this demo, and with the help of a poster (Fig. S5 in the supplemental material),[59] was used to help explain a number of flow characteristics commonly found in microfluidics, albeit in a "stripped back" manner devoid of any real depth, jargon, or equations. Specifically, the workstation was described thus: (1) laminar flow was described as being the way in which fluid streams, on a small-scale as in microfluidic devices, flow side-by-side; (2) diffusive mixing was discussed as being the way in which two such laminar streams containing

chemicals slowly move into each other as they flow alongside each other, allowing their mixing, with additional help from hand movements to demonstrate the process; (3) gradient formation by continuously splitting, recombining and diffusive mixing of the laminar flow streams; (4) the use of such gradients for simultaneously observing the effects of drugs or other chemicals on cells within a chamber (or chambers), with examples stated as including the testing of different concentrations of cancer drugs on cancer cells. To aid in explaining this latter point, a glass microfluidic device used to perform research experiments at Hull[63] was also presented to the students in order to relate the real device to the oversized platform.

Following these explanations, the students were separated into pairs and asked to perform an activity using device design 2 (the "juice chip"). The juice chip was set up such that a syringe containing yellow coloured fruit juice (e.g. orange juice or pineapple juice) was attached to one inlet of the device, while a syringe containing red coloured fruit juice (e.g. cranberry juice or blackcurrent juice) was attached to the other inlet. The two students in a pair took hold of one syringe each, and were instructed to push the syringe plungers and try to form a gradient in the microfluidic channels (Fig. 9c), as was being demonstrated in device 1. The channels in the oversized juice chip had been milled with relatively large dimensions not only to allow good visualisation of the fluids within them, but to produce little backpressure and so make it easier for the students to push the syringes and generate flow in the channels. As the outlet reservoirs became full, they would be emptied using a 20 mL disposable syringe (BD Plastipak) with a syringe needle or cut-to-size pipette tip attached.

Although a simple-sounding task, the application of different pressures from the two students added a high degree of challenge to the proceedings that let them develop an understanding of laminar flow and of how small changes in pressure can have a large effect on the flow regime, with the gradient shifting to the left and right in the device. With time and patience, however, most student pairs were able to produce a fairly steady gradient across the chip, with the pair who produced the best gradient receiving a treat (a packet of sweets/candy), and the students generally enjoyed the hands-on activity and challenge it posed.

E. Tissue-on-a-chip: *Oversized tissue chip*

Microfluidic devices have become very popular for the study of biological tissues,[83-86] and for the mimicry of tissues and organs,[4, 74, 85-92] thanks to the ability to continuously flush nutrients through microchannels to the tissue. This better mimics the *in vivo* environment compared to conventional flask-based methods, and research is moving towards the development of a "human-on-a-chip" that allows fluidic contact between tissues or organ-mimicking cell structures in a microfluidic platform.[62, 90, 93-95] The University of Hull has been working with tissue on-chip for

many years now, having developed devices for the on-chip culture of tissue biopsies,[64, 96] toxicity studies,[97-99] dissociation and detection of antibody-labelled cells from tumour cells,[100] perfusion of viable heart tissue with electrochemical monitoring,[101, 102] and the study of radiation-induced cell death in tissue.[103] With this established history microfluidics-based tissue research, we were keen to demonstrate some of the basic concepts of the field to the school students.

The microfluidic devices employed at the University of Hull have largely followed a similar design concept,[64] in that a chamber containing a tissue biopsy is situated in the path of a microchannel such that media or reagents can be flushed over the tissue, allowing the effect of stimuli to be observed on the tissue both visually (via microscopy and fluorescence microscopy) and by collecting effluent from the outlet of the chip for analysis of biomolecules released from the tissue. With this in mind, an oversized tissue chip was fabricated from PMMA for the workstation, featuring a lidded central chamber n the flow path of a single microchannel (see the section 2.6 and Fig. 10a). The setup and the microfluidic procedures were explained to the school students in terms of drug studies for cancer treatment, with the help of a poster (see Fig. S6 in the supplemental material)[59] and an actual glass microfluidic tissue chip that had been used to perform experiments at Hull.[64] Specifically, the concept and setup was explained thus: (1) with the aid of the real chip and the oversized chips, it was explained how a piece of cancerous tissue, taken from a tumour biopsy, can be placed in the tissue chamber of the chip; (2) a solution containing cancer drugs can be pumped through the chip, thereby exposing the tumour to the drug; (3) how the effect on the tissue can be observed directly via a microscope, in terms of a positive result (i.e. cancerous tissue is killed) or negative result (i.e. there is no effect on the tissue, or the tissue even grows), and/or the solution can be collected from the outlet of the chip and analysed to determine whether any chemicals had been released by the tumour that would indicate a positive or negative result; (4) the analogous experiment involving the oversized chip was explained, with pH paper representing tissue, and solutions of lemon juice and water representing different drugs to be tested.

To perform the experiment, the "tissue" chamber of the oversized device was opened and a piece of universal pH paper, mimicking a piece of tissue, would be placed in the microfluidic channel, then the lid closed The inlet tubing would be placed in a beaker of either the lemon juice or water, and a student would then pull on the plunger of the 20 mL syringe attached to the outlet tubing, drawing the solution through the microchannel and so across the pH paper via negative pressure (to avoid the risk of spraying acidic lemon juice into someone's eyes, as could occur if positive pressure was applied and a seal burst somewhere in the chip or tubing) (Fig. 10b). Lemon juice would thus turn the pH paper red, indicating a negative effect of the "drug" on the "tissue", while water

would turn the pH paper green, indicating a positive effect of the drug (Fig. 10c). Whether the solution consisted of water or lemon juice was chosen at random, and between each test the chip would be flushed with air and the inside of the chamber dried with Kimwipe roll. The students generally enjoyed the activity, commenting that it was "*interesting*" and "*well explained*", with one student writing in their feedback that "*It has given me an insight into the treatments of cancer and testing on cancerous tissue*".

V. DISCUSSION

During the workshop, the level of engagement of the students with the activities and their enjoyment of them could be gauged to an extent, with a largely positive vibe present throughout. In order to better quantify their response to the event, the students were given a questionnaire that they filled in and submitted at the end of their session. The questionnaire, which can be found in the supplemental material,[59] was designed to determine how the students found the event in general as well as the individual workstations, as well as whether they had previously heard of lab-on-a-chip and if they felt they had a better understanding of the field by the end of the workshop. Responses were garnered from 51 students in total. Unfortunately, a couple of groups of students were unable to perform all of the activities during their session due to time constraints, hence some answers were not given for individual activities, while some of the questions in the questionnaire were simply not answered. Returned responses with no answers have been eliminated from the following analysis and discussion, although the raw data from the 51 students can be found in Tables S1-S3 in the supplemental material.[59]

The results from the questionnaire were compiled and are presented here as graphs. Fig. 11a shows the response to the question "*How did you find the workshop?*", with a choice of answers ranging from *Very good* to *Very bad*. On the whole, nearly half of students found the workshop to be *Very good* and nearly half to be *Good*, with only one student judging it to be *Okay* and one student not providing an answer. Nobody found the workshop to be *Bad* or *Very bad*. Thus, response to the workshop was very positive, with a 98 % satisfaction rating. The students were then asked to judge how well the individual activities were explained on the same *Very good*-to-*Very bad* scale, as shown in Fig. 11b. On the whole, the workstation explanations were judged as being *Very good* or *Good*, though a portion of students thought they were only *Okay*. The tissue, chocolate, and gradient mixing explanations were considered to be bad by one student each, but on the whole the response was generally very positive, with a minimum satisfaction rating of 73 % (based on *Very good* and *Good* responses) for any of the activity explanations. The chocolate moulding activity was considered to be the best explained (94 % rating of *Very good* or *Good*), with the pantograph milling exercise also performing particularly strongly (94 % rating of *Very good* or *Good*).

Fig. 11c indicates which workstation activity the students found to be their favourite. Perhaps unsurprisingly given the treat-based nature of the exercise, the chocolate moulding workstation was by far the most popular, with more than half (56.5 %) of the students preferring this station above the others. The other stations' popularity each accounted for 8.7 - 13.0 % of the favourites among the students.

The students were further asked to state whether they had heard of lab-on-a-chip before attending the workshop, to which the response was a unanimous "*No*". However, upon undertaking the various activities and explanations of lab-on-a-chip, 94 % of students answered "*Yes*" the question "*Do you feel you have a better understanding of what lab-on-a-chip is now?*". This, combined with the fact that 100 % of students who responded to the question "Did you find the workshop interesting?" answered "*Yes*", demonstrated that the main two priorities of the workshop as a whole, to provide an interesting and exciting experience that introduced students to the field of lab-on-a-chip, had been realised.

The survey indicated that, on the whole, the workshop and the individual workstations were a rousing success. However, the largely multiple choice survey only offered limited feedback about specific aspects of the workshop. For example, it could have been anticipated that the students, who were unlikely to have heard of lab-on-a-chip or microfluidics before, would indicate that they now had a better understanding of what the field was. In later workshop events, an updated survey could be employed that asks more open-ended questions, forcing the students to write specific answers rather than simply tick a box, even asking students to state in their own words what different terms were and what they had learned. It could even perhaps take the form of a short test, although this could potentially take some of the "fun factor" away from the overall event. Furthermore, such open-ended questions and short tests require more time, which was already very limited at the workshop, hence a compromise between multiple choice questions and a few *select* open-ended questions would likely be more ideal. The same critique can also be applied to the questions about the workstations, since there was little information about *why* some activities were more popular than others. Further to this, the answers may have been influenced by factors other than the activity itself. For example, while the chocolate station was the favourite, this may have been swayed by the fact that the students received a chocolate treat; if there was no treat at the end, would the workstation still be rated so highly based purely on the actual activity? While an option was given for the students to explain why a specific workstation was their favourite, only a handful actually provided such feedback. As with the questions about lab-on-a-chip and the workshop in general, this would benefit from requiring specific feedback for each workstation, but again this would need to compromise with the need for a fast questionnaire that can be completed

in the strict timeframe of the workshop. Alternatively, an agreement could be made with the students' teacher(s), such that the questionnaire can be taken away, completed by the students shortly after the workshop, and then returned to the workshop organisers at a later date. All of these aspects will need to be considered prior to the next such workshop.

In addition to the questionnaire, the experiences of the demonstrators and supervisors of the workshop, in addition to comments made by students and teachers during the event, can be used to gauge the attitudes towards how the workshop was run and to the individual workstations. Most of the children genuinely appeared to enjoy the workshop and participation in the various activities, though as is only natural, some students were more inquisitive and willing to engage than others. The ability of the demonstrators to gauge the response of the students actually led to the introductions provided for each workstation developing over the course of the day, based on overheard comments and by judging the expressions of the students. It soon became apparent that in many cases it was better to provide only an overview of the technique being described, and to focus on "*how a technique works*" rather than "*why a technique works in the way it does*", without going into much depth or theory. The impression gleaned by the demonstrators was that by approaching the description is such a why the students were largely to understand the core concepts of each activity. For example, students performing the chocolate moulding activity seemed to come away from the workstation with the idea of how injection moulding worked: melting a polymer, injecting it into a mould, and letting it cool to form the device, but without necessarily understanding how an actual injection moulding machine worked. The same can be said for the pantograph activity, where students understood that a cutting tool, controlled by a computer onto which a design is uploaded, is used to cut that design into a substrate/workpiece, but again without going into detail about how the actual CNC milling machine works. Thus, at each workstation the introduction and amount of detail had to be adapted until a level was reached such that the students could grasp the main concepts.

One instance was noted in which a researcher visited one of the workstations early in the day where, upon seeing a microfluidic device being described with which they had extensive experience, the researcher attempted to give a more in-depth understanding of the concepts behind the chip, only to end up using technical terms and concepts to which the students were unfamiliar. This particular student group subsequently left that workstation notably confused as to the purpose of the chip and how it worked. A similar scenario was observed at another workstation during a description of the applications of a microfluidic device, in which the teacher in charge of the students remarked that the demonstrator was using terms unfamiliar to the students. These examples reiterated the

fact that descriptions and discussions needed to be stripped down to jargon-free overviews that stated only the core concepts without going into any great depth or technical detail.

The engagement of the students with the workstation activities was largely noted to be very successful. One thing that became apparent was that the more hands-on an activity was, the more enjoyable it appeared. Despite the chocolate treat, the students clearly engaged very well with the chocolate moulding activity. Likewise, the pantograph milling station also seemed particularly well-liked, and despite arguably being the most disconnected example in terms of the technique it purports to describe, the students nonetheless left with a good, basic understanding of how chips can be fabricated by milling. Perhaps it would be possible to develop a new workshop activity that describes in more detail how CNC milling actually works, but the pantograph actually represented an excellent example of bridging "fun and hands-on" with "educational". Conversely, while an activity such as the oversized tissue chip offered a more accurate example of how a microfluidic device works, the hands-on component was quite limited. Interestingly, it could be noted how some of the students actually preferred to understand more about such techniques from an intellectual standpoint rather than the hands-on aspect. With over 50 students undertaking the workshop, however, the more hands-on activities were overall more popular, hence the tissue activity would benefit from a more practical aspect, which could include collecting different "tissues" from different sources before testing them on the device with multiple reagents. A further problem encountered was that "rough handling" by students resulted, in one instance, in the tubing being pulled out of the chip, resulting in one group missing this activity while the tubing was reattached. Robustness of apparatus is therefore an extra factor that must be considered, particularly for objects such as oversized chips which feature tubing and syringes that can become unattached.

It had been considered that the paper microfluidics station, which involved drawing on paper with wax crayons, station may have been looked on as being "childish" by the students, but actually this example largely proved very popular, particularly when the students were asked to draw their own designs and apply the coloured liquids to them. The fluid manipulation and laminar flow assay examples helped to explain these concepts, but there is scope for improvement and the activity would perhaps benefit from a stronger link to actual μPADs, possibly incorporating reagents for analysing simple samples as described in previously published articles.[48-51] Furthermore, the recent acquisition of a wax printer means that more sophisticated devices could be fabricated for these demonstrations, but the procedures used here nonetheless provide a very useful, minimalist approach.

Students enjoyed the interesting patterns of the oversized gradient devices, and the challenge of attempting to generate their own gradient in the "juice chip", but again this activity has scope for more of a link to some of the applications. This could be achieved by modifying the chip design to include a chamber across which the gradient can be applied, with cell substitutes (e.g. pH paper) incorporated into the chamber to demonstrate the effect of a gradient of a "drug" on single "cells". Furthermore, the channels in the juice chip exhibited very little backpressure, meaning that the system was very susceptible to slight differences in pressure from the inlets, thereby requiring very careful manipulation of the inlet syringes. For most students, this took a little getting used to but after some practice they could generate a gradient, and could observe the phenomena of laminar flow and diffusive mixing, while appreciating how small differences in inlet pressure can affect the system. Some more heavy handed students, however, did struggle to obtain a "nice looking" gradient, but nevertheless appeared to enjoy their attempts.

While some aspects of the workshop and the activities could stand to be improved in later iterations based on the student responses and experiences of the demonstrators and supervisors, the event was on the whole very successful. To reiterate points commented on in the introduction of this paper, and discussed in the previous paragraphs, the engagement of the students (aged 13-14) with the activities and concepts increased with the more hands-on examples and with descriptions that avoided technical jargon or in-depth detail that went beyond the core information. These experiences will help to plan future events, which we anticipate will utilise the same workstation activities, albeit perhaps updated in some cases.

More information about the Hull Science Festival 2015 is available online,[58] while photographs taken from the Lab-on-a-Chip workshop and from the Festival in general can be found on Flickr.[104]

VI. CONCLUSIONS

We have developed a series of activities for introducing school students to the field of microfluidics and lab-on-a-chip, by using hands-on props that were analogous to various fabrication processes and applications. The workshop was produced as part of a larger Hull Science Festival 2015 event, taking place over several days. The lab-on-a-chip workstations were designed to highlight some of the facilities and research performed at the University of Hull, in particular CNC micromilling (via the use of a pantograph), polymer injection moulding (via the moulding of molten chocolate), fabrication and operation of paper microfluidic devices (via wax crayon designs), gradient formation and flow regimes (via an oversized gradient chip), and on-chip tissue analysis (via an oversized tissue chip).

The students responded well to the workshop, and importantly their feedback indicated that they found it both interesting and informative. The feedback also indicated points that could be worked on and improved for subsequent workshops. As scientific outreach events become more popular, an increase in the number of microfluidics and lab-on-a-chip workshops being delivered can be expected to increase, and we hope that the hands-on activities described here can help to provide ideas and inspiration for such events around the world.

ACKNOWLEDGEMENTS

The authors acknowledge advice, suggestions, ideas, and assistance from Gary Kipling, Nathaniel J. Brown, Stephen J. Haswell, John Greenman, Charlotte Dyer, Ruth Bower, Alexander Iles, Ruchi Gupta, and Mark Lorch. Mike Park is thanked for the photographs taken during the workshop. Nigel Parkin and Chris Lloyd are thanked for the provision and fabrication of materials and apparatus.

REFERENCES

1. M. D. Tarn and N. Pamme, in *Elsevier Reference Module in Chemistry, Molecular Sciences and Chemical Engineering*, edited by J. Reedijk (Elsevier, Waltham, MA, 2013).
2. P. N. Nge, C. I. Rogers and A. T. Woolley, "Advances in microfluidic materials, functions, integration, and applications" Chem. Rev. **113** (4), 2550-2583 (2013).
3. G. M. Whitesides, "The origins and the future of microfluidics" Nature **442** (7101), 368-373 (2006).
4. E. K. Sackmann, A. L. Fulton and D. J. Beebe, "The present and future role of microfluidics in biomedical research" Nature **507** (7491), 181-189 (2014).
5. D. R. Reyes, D. Iossifidis, P.-A. Auroux and A. Manz, "Micro Total Analysis Systems. 1. Introduction, theory, and technology" Anal. Chem. **74** (12), 2623-2636 (2002).
6. P.-A. Auroux, D. Iossifidis, D. R. Reyes and A. Manz, "Micro Total Analysis Systems. 2. Analytical standard operations and applications" Anal. Chem. **74** (12), 2637-2652 (2002).
7. T. Vilkner, D. Janasek and A. Manz, "Micro Total Analysis Systems. Recent developments" Anal. Chem. **76** (12), 3373-3386 (2004).
8. P. S. Dittrich, K. Tachikawa and A. Manz, "Micro Total Analysis Systems. Latest advancements and trends" Anal. Chem. **78** (12), 3887-3908 (2006).
9. J. West, M. Becker, S. Tombrink and A. Manz, "Micro Total Analysis Systems: Latest achievements" Anal. Chem. **80** (12), 4403-4419 (2008).

10. A. Arora, G. Simone, G. B. Salieb-Beugelaar, J. T. Kim and A. Manz, "Latest developments in Micro Total Analysis Systems" Anal. Chem. **82** (12), 4830-4847 (2010).

11. G. B. Salieb-Beugelaar, G. Simone, A. Arora, A. Philippi and A. Manz, "Latest developments in microfluidic cell biology and analysis systems" Anal. Chem. **82** (12), 4848-4864 (2010).

12. M. L. Kovarik, P. C. Gach, D. M. Ornoff, Y. Wang, J. Balowski, L. Farrag and N. L. Allbritton, "Micro Total Analysis Systems for cell biology and biochemical assays" Anal. Chem. **84** (2), 516-540 (2012).

13. M. L. Kovarik, D. M. Ornoff, A. T. Melvin, N. C. Dobes, Y. Wang, A. J. Dickinson, P. C. Gach, P. K. Shah and N. L. Allbritton, "Micro Total Analysis Systems: Fundamental advances and applications in the laboratory, clinic, and field" Anal. Chem. **85** (2), 451-472 (2013).

14. C. T. Culbertson, T. G. Mickleburgh, S. A. Stewart-James, K. A. Sellens and M. Pressnall, "Micro Total Analysis Systems: Fundamental advances and biological applications" Anal. Chem. **86** (1), 95-118 (2014).

15. L. R. Volpatti and A. K. Yetisen, "Commercialization of microfluidic devices" Trends Biotechnol. **32** (7), 347-350 (2014).

16. C. D. Chin, V. Linder and S. K. Sia, "Commercialization of microfluidic point-of-care diagnostic devices" Lab Chip **12** (12), 2118-2134 (2012).

17. FluidicMEMS website, *http://fluidicmems.com/list-of-microfluidics-lab-on-a-chip-and-biomems-companies/*, accessed 2015.

18. Microfluidics Directory website, Microfluidics Consortium, *http://www.microfluidicsdirectory.com/home.html*, accessed 2015.

19. C. W. T. Yang, E. Ouellet and E. T. Lagally, "Using inexpensive Jell-O chips for hands-on microfluidics education" Anal. Chem. **82** (13), 5408-5414 (2010).

20. D. C. Duffy, J. C. McDonald, O. J. A. Schueller and G. M. Whitesides, "Rapid prototyping of microfluidic systems in poly(dimethylsiloxane)" Anal. Chem. **70** (23), 4974-4984 (1998).

21. J. C. McDonald, D. C. Duffy, J. R. Anderson, D. T. Chiu, H. Wu, O. J. A. Schueller and G. M. Whitesides, "Fabrication of microfluidic systems in poly(dimethylsiloxane)" Electrophoresis **21** (1), 27-40 (2000).

22. T. A. Davis, S. L. Athey, M. L. Vandevender, C. L. Crihfield, C. C. E. Kolanko, S. Shao, M. C. G. Ellington, J. K. Dicks, J. S. Carver and L. A. Holland, "Electrolysis of water in the secondary school science laboratory with inexpensive microfluidics" J. Chem. Educ. **92** (1), 116-119 (2015).

23. D. Bardin and A. P. Lee, "Low-cost experimentation for the study of droplet microfluidics" Lab Chip **14** (20), 3978-3986 (2014).

24. M. Jimenez and H. L. Bridle, "Angry pathogens, how to get rid of them: introducing microfluidics for waterborne pathogen separation to children" Lab Chip **15** (4), 947-957 (2015).

25. D. Nguyen, J. McLane, V. Lew, J. Pegan and M. Khine, "Shrink-film microfluidic education modules: Complete devices within minutes" Biomicrofluidics **5** (2), 022209 (2011).

26. A. Grimes, D. N. Breslauer, M. Long, J. Pegan, L. P. Lee and M. Khine, "Shrinky-Dink microfluidics: rapid generation of deep and rounded patterns" Lab Chip **8** (1), 170-172 (2008).

27. Z. V. Feng, K. R. Edelman and B. P. Swanson, "Student-fabricated microfluidic devices as flow reactors for organic and inorganic synthesis" J. Chem. Educ. **92** (4), 723-727 (2015).

28. M. Hemling, J. A. Crooks, P. M. Oliver, K. Brenner, J. Gilbertson, G. C. Lisensky and D. B. Weibel, "Microfluidics for high school chemistry students" J. Chem. Educ. **91** (1), 112-115 (2014).

29. T. C. DeVore, B. H. Augustine, A. M. Christenson and G. W. Corder, "A photolithography laboratory experiment for general chemistry students" J. Chem. Educ. **80** (2), 183-186 (2003).

30. K. L. Berkowski, K. N. Plunkett, Q. Yu and J. S. Moore, "Introduction to photolithography: Preparation of microscale polymer silhouettes" J. Chem. Educ. **82** (9), 1365-1369 (2005).

31. P. K. Yuen and V. N. Goral, "Low-cost rapid prototyping of whole-glass microfluidic devices" J. Chem. Educ. **89** (10), 1288-1292 (2012).

32. Y. Zheng, J. Nguyen, Y. Wei and Y. Sun, "Recent advances in microfluidic techniques for single-cell biophysical characterization" Lab Chip **13** (13), 2464-2483 (2013).

33. M. C. Chia, C. M. Sweeney and T. W. Odom, "Chemistry in microfluidic channels" J. Chem. Educ. **88** (4), 461-464 (2011).

34. P. A. E. Piunno, A. Zetina, N. Chu, A. J. Tavares, M. O. Noor, E. Petryayeva, U. Uddayasankar and A. Veglio, "A comprehensive microfluidics device construction and characterization module for the advanced undergraduate analytical chemistry laboratory" J. Chem. Educ. **91** (6), 902-907 (2014).

35. W. Mielczarek, T. J. Aspray, F. Mallevre, M. Jimenez, J. McGrath, P. Cameron, H. Bridle and M. Kersaudy-Kerhoas, ""Microworld and microflows": Initiating school children to microfluidics" presented at the 4th European Conference on Microfluidics (μFlu'14), Limerick, Ireland, 2014.

36. M. Junkin and S. Tay, "Microfluidic single-cell analysis for systems immunology" Lab Chip **14** (7), 1246-1260 (2014).

37. J. Nilsson, M. Evander, B. Hammarstrom and T. Laurell, "Review of cell and particle trapping in microfluidic systems" Anal. Chim. Acta **649** (2), 141-157 (2009).

38. G. Velve-Casquillas, M. Le Berre, M. Piel and P. T. Tran, "Microfluidic tools for cell biological research" Nano Today **5** (1), 28-47 (2010).

39. I. Meyvantsson and D. J. Beebe, "Cell culture models in microfluidic systems" Annu. Rev. Anal. Chem. **1** (1), 423-449 (2008).

40. S. Teerasong and R. L. McClain, "A student-made microfluidic device for electrophoretic separation of food dyes" J. Chem. Educ. **88** (4), 465-467 (2011).

41. T.-C. Chao, S. Bhattacharya and A. Ros, "Microfluidic gel electrophoresis in the undergraduate laboratory applied to food analysis" J. Chem. Educ. **89** (1), 125-129 (2012).

42. P. A. E. Piunno, A. Zetina, N. Chu, A. J. Tavares, M. O. Noor, E. Petryayeva, U. Uddayasankar and A. Veglio, "A comprehensive microfluidics device construction and characterization module for the advanced undergraduate analytical chemistry laboratory" J. Chem. Educ. **91** (6), 902-907 (2014).

43. B. Giri, R. R. Peesara, N. Yanagisawa and D. Dutta, "Undergraduate laboratory module for implementing ELISA on the high performance microfluidic platform" J. Chem. Educ. **92** (4), 728-732 (2015).

44. Y. Fintschenko, "Education: A modular approach to microfluidics in the teaching laboratory" Lab Chip **11** (20), 3394-3400 (2011).

45. D. M. Cate, J. A. Adkins, J. Mettakoonpitak and C. S. Henry, "Recent developments in paper-based microfluidic devices" Anal. Chem. **87** (1), 19-41 (2015).

46. A. K. Yetisen, M. S. Akram and C. R. Lowe, "Paper-based microfluidic point-of-care diagnostic devices" Lab Chip **13** (12), 2210-2251 (2013).

47. A. W. Martinez, S. T. Phillips, M. J. Butte and G. M. Whitesides, "Patterned paper as a platform for inexpensive, low-volume, portable bioassays" Angew. Chem. Int. Ed. **46** (8), 1318-1320 (2007).

48. L. Cai, Y. Wu, C. Xu and Z. Chen, "A simple paper-based microfluidic device for the determination of the total amino acid content in a tea leaf extract" J. Chem. Educ. **90** (2), 232-234 (2013).

49. R. R. Ravgiala, S. Weisburd, R. Sleeper, A. Martinez, D. Rozkiewicz, G. M. Whitesides and K. A. Hollar, "Using paper-based diagnostics with high school students to model forensic investigation and colorimetric analysis" J. Chem. Educ. **91** (1), 107-111 (2014).

50. B. Wang, Z. Lin and M. Wang, "Fabrication of a paper-based microfluidic device to readily determine nitrite ion concentration by simple colorimetric assay" J. Chem. Educ. **92** (4), 733-736 (2015).

51. M. T. Koesdjojo, S. Pengpumkiat, Y. Wu, A. Boonloed, D. Huynh, T. P. Remcho and V. T. Remcho, "Cost effective paper-based colorimetric microfluidic devices and mobile phone camera readers for the classroom" J. Chem. Educ. **92** (4), 737-741 (2015).

52. T. Bowman, J. Frechette and G. Drazer, "Force driven separation of drops by deterministic lateral displacement" Lab Chip **12** (16), 2903-2908 (2012).

53. T. J. Bowman, G. Drazer and J. Frechette, "Inertia and scaling in deterministic lateral displacement" Biomicrofluidics **7** (6), 064111 (2013).

54. L. R. Huang, E. C. Cox, R. H. Austin and J. C. Sturm, "Continuous particle separation through deterministic lateral displacement" Science **304** (5673), 987-990 (2004).

55. J. McGrath, M. Jimenez and H. Bridle, "Deterministic lateral displacement for particle separation: a review" Lab Chip **14** (21), 4139-4158 (2014).

56. H. Bridle, B. Miller and M. P. Y. Desmulliez, "Application of microfluidics in waterborne pathogen monitoring: A review" Water Res. **55**, 256-271 (2014).

57. H. Bridle, M. Kersaudy-Kerhoas, B. Miller, D. Gavriilidou, F. Katzer, E. A. Innes and M. P. Y. Desmulliez, "Detection of Cryptosporidium in miniaturised fluidic devices" Water Res. **46** (6), 1641-1661 (2012).

58. Hull Science Festival 2015 website, University of Hull, *www2.hull.ac.uk/science/sciencefestival.aspx*, accessed 2015.

59. See supplemental material at **[URL will be inserted by AIP]** for the questionnaire given to school students, the raw data taken from the questionnaire responses, and the A4 posters used to explain the activity and its background at each workstation.

60. C. M. B. Ho, S. H. Ng, K. H. H. Li and Y.-J. Yoon, "3D printed microfluidics for biological applications" Lab Chip **15** (18), 3627-3637 (2015).

61. S. K. W. Dertinger, D. T. Chiu, N. L. Jeon and G. M. Whitesides, "Generation of gradients having complex shapes using microfluidic networks" Anal. Chem. **73** (6), 1240-1246 (2001).

62. H. E. Abaci and M. L. Shuler, "Human-on-a-chip design strategies and principles for physiologically based pharmacokinetics/pharmacodynamics modeling" Integr. Biol. **7** (4), 383-391 (2015).

63. J. García-Alonso, R. F. Fakhrullin, V. N. Paunov, Z. Shen, J. D. Hardege, N. Pamme, S. J. Haswell and G. M. Greenway, "Microscreening toxicity system based on living magnetic yeast and gradient chips" Anal. Bioanal. Chem. **400** (4), 1009-1013 (2011).

64. S. M. Hattersley, C. E. Dyer, J. Greenman and S. J. Haswell, "Development of a microfluidic device for the maintenance and interrogation of viable tissue biopsies" Lab Chip **8** (11), 1842-1846 (2008).

65. D. J. Guckenberger, T. E. de Groot, A. M. D. Wan, D. J. Beebe and E. W. K. Young, "Micromilling: a method for ultra-rapid prototyping of plastic microfluidic devices" Lab Chip **15** (11), 2364-2378 (2015).

66. H. Becker and C. Gärtner, "Polymer microfabrication technologies for microfluidic systems" Anal. Bioanal. Chem. **390** (1), 89-111 (2008).

67. J. Giboz, T. Copponnex and P. Mélé, "Microinjection molding of thermoplastic polymers: a review" J. Micromech. Microeng. **17** (6), R96-R109 (2007).

68. J.-S. Chu, M. D. Gilchrist and N. Zhang, in *Encyclopedia of Microfluidics and Nanofluidics*, edited by D. Li (Springer US, 2014), pp. 1-18.

69. H. Becker and L. E. Locascio, "Polymer microfluidic devices" Talanta **56** (2), 267-287 (2002).

70. U. M. Attia, S. Marson and J. R. Alcock, "Micro-injection moulding of polymer microfluidic devices" Microfluid. Nanofluid. **7** (1), 1-28 (2009).

71. P. Lisowski and P. Zarzycki, "Microfluidic paper-based analytical devices (μPADs) and Micro Total Analysis Systems (μTAS): Development, applications and future trends" Chromatographia **76** (19-20), 1201-1214 (2013).

72. A. W. Martinez, "Microfluidic paper-based analytical devices: from POCKET to paper-based ELISA" Bioanalysis **3** (23), 2589-2592 (2011).

73. K. Yamada, T. G. Henares, K. Suzuki and D. Citterio, "Paper-based inkjet-printed microfluidic analytical devices" Angew. Chem. Int. Ed. **54** (18), 5294-5310 (2015).

74. X. Li, A. V. Valadez, P. Zuo and Z. Nie, "Microfluidic 3D cell culture: potential application for tissue-based bioassays" Bioanalysis **4** (12), 1509-1525 (2012).

75. A. Dawson, J. Cleland, S. Jones and T. McCreedy, ""Paper microfluidics for the detection of iron(II) in human serum samples", in preparation (2016).

76. E. Carrilho, A. W. Martinez and G. M. Whitesides, "Understanding wax printing: A simple micropatterning process for paper-based microfluidics" Anal. Chem. **81** (16), 7091-7095 (2009).

77. C. Renault, J. Koehne, A. J. Ricco and R. M. Crooks, "Three-dimensional wax patterning of paper fluidic devices" Langmuir **30** (23), 7030-7036 (2014).

78. T. M. Keenan and A. Folch, "Biomolecular gradients in cell culture systems" Lab Chip **8** (1), 34-57 (2008).

79. A. G. Toh, Z. P. Wang, C. Yang and N.-T. Nguyen, "Engineering microfluidic concentration gradient generators for biological applications" Microfluid. Nanofluid. **16** (1-2), 1-18 (2014).

80. E. Berthier and D. J. Beebe, "Gradient generation platforms: new directions for an established microfluidic technology" Lab Chip **14** (17), 3241-3247 (2014).

81. S. Kim, H. J. Kim and N. L. Jeon, "Biological applications of microfluidic gradient devices" Integr. Biol. **2** (11-12), 584-603 (2010).

82. B. G. Chung and J. Choo, "Microfluidic gradient platforms for controlling cellular behavior" Electrophoresis **31** (18), 3014-3027 (2010).

83. A. Webster, J. Greenman and S. J. Haswell, "Development of microfluidic devices for biomedical and clinical application" J. Chem. Technol. Biotechnol. **86** (1), 10-17 (2011).

84. F. Tanweer, V. L. Green, N. D. Stafford and J. Greenman, "Application of microfluidic systems in management of head and neck squamous cell carcinoma" Head Neck **35** (5), 756-763 (2013).

85. V. Sivagnanam and M. A. M. Gijs, "Exploring living multicellular organisms, organs, and tissues using microfluidic systems" Chem. Rev. **113** (5), 3214-3247 (2013).

86. E. W. K. Young, "Cells, tissues, and organs on chips: challenges and opportunities for the cancer tumor microenvironment" Integr. Biol. **5** (9), 1096-1109 (2013).

87. S. N. Bhatia and D. E. Ingber, "Microfluidic organs-on-chips" Nat. Biotechnol. **32** (8), 760-772 (2014).

88. Y. Huang, J. C. Williams and S. M. Johnson, "Brain slice on a chip: opportunities and challenges of applying microfluidic technology to intact tissues" Lab Chip **12** (12), 2103-2117 (2012).

89. D. Huh, Y.-s. Torisawa, G. A. Hamilton, H. J. Kim and D. E. Ingber, "Microengineered physiological biomimicry: Organs-on-Chips" Lab Chip **12** (12), 2156-2164 (2012).

90. D. Huh, G. A. Hamilton and D. E. Ingber, "From 3D cell culture to organs-on-chips" Trends Cell Biol. **21** (12), 745-754 (2011).

91. C. Moraes, G. Mehta, S. Lesher-Perez and S. Takayama, "Organs-on-a-chip: A focus on compartmentalized microdevices" Ann. Biomed. Eng. **40** (6), 1211-1227 (2012).

92. A. D. van der Meer and A. van den Berg, "Organs-on-chips: breaking the in vitro impasse" Integr. Biol. **4** (5), 461-470 (2012).

93. C. Zhang, Z. Zhao, N. A. Abdul Rahim, D. van Noort and H. Yu, "Towards a human-on-chip: Culturing multiple cell types on a chip with compartmentalized microenvironments" Lab Chip **9** (22), 3185-3192 (2009).

94. I. Maschmeyer, A. K. Lorenz, K. Schimek, T. Hasenberg, A. P. Ramme, J. Hubner, M. Lindner, C. Drewell, S. Bauer, A. Thomas, N. S. Sambo, F. Sonntag, R. Lauster and U. Marx, "A four-organ-chip for interconnected long-term co-culture of human intestine, liver, skin and kidney equivalents" Lab Chip **15** (12), 2688-2699 (2015).

95. C. Moraes, J. M. Labuz, B. M. Leung, M. Inoue, T.-H. Chun and S. Takayama, "On being the right size: scaling effects in designing a human-on-a-chip" Integr. Biol. **5** (9), 1149-1161 (2013).

96. A. Webster, C. E. Dyer, S. J. Haswell and J. Greenman, "A microfluidic device for tissue biopsy culture and interrogation" Anal. Methods **2** (8), 1005-1007 (2010).

97. S. M. Hattersley, J. Greenman and S. J. Haswell, "Study of ethanol induced toxicity in liver explants using microfluidic devices" Biomed. Microdevices **13** (6), 1005-1014 (2011).

98. S. M. Hattersley, D. C. Sylvester, C. E. Dyer, N. D. Stafford, S. J. Haswell and J. Greenman, "A microfluidic system for testing the responses of head and neck squamous cell carcinoma tissue biopsies to treatment with chemotherapy drugs" Ann. Biomed. Eng. **40** (6), 1277-1288 (2012).

99. D. Sylvester, S. M. Hattersley, N. D. Stafford, S. J. Haswell and J. Greenman, "Development of microfluidic-based analytical methodology for studying the effects of chemotherapy agents on cancer tissue" Curr. Anal. Chem. **9** (1), 2-8 (2013).

100. J. Woods, P. T. Docker, C. E. Dyer, S. J. Haswell and J. Greenman, "On-chip integrated labelling, transport and detection of tumour cells" Electrophoresis **32** (22), 3188-3195 (2011).

101. L.-T. Cheah, Y.-H. Dou, A.-M. L. Seymour, C. E. Dyer, S. J. Haswell, J. D. Wadhawan and J. Greenman, "Microfluidic perfusion system for maintaining viable heart tissue with real-time electrochemical monitoring of reactive oxygen species" Lab Chip **10** (20), 2720-2726 (2010).

102. L. T. Cheah, I. Fritsch, S. J. Haswell and J. Greenman, "Evaluation of heart tissue viability under redox-magnetohydrodynamics conditions: Toward fine-tuning flow in biological microfluidics applications" Biotechnol. Bioeng. **109** (7), 1827-1834 (2012).

103. S. D. Carr, V. L. Green, N. D. Stafford and J. Greenman, "Analysis of radiation-induced cell death in head and neck squamous cell carcinoma and rat liver maintained in microfluidic devices" Otolaryngol. Head Neck Surg. **150** (1), 73-80 (2014).

104. Hull Science Festival 2015 #HullSciFest photograph album on Flickr, www.flickr.com/photos/universityofhull/albums/72157651111146578/page2/, accessed 2015.

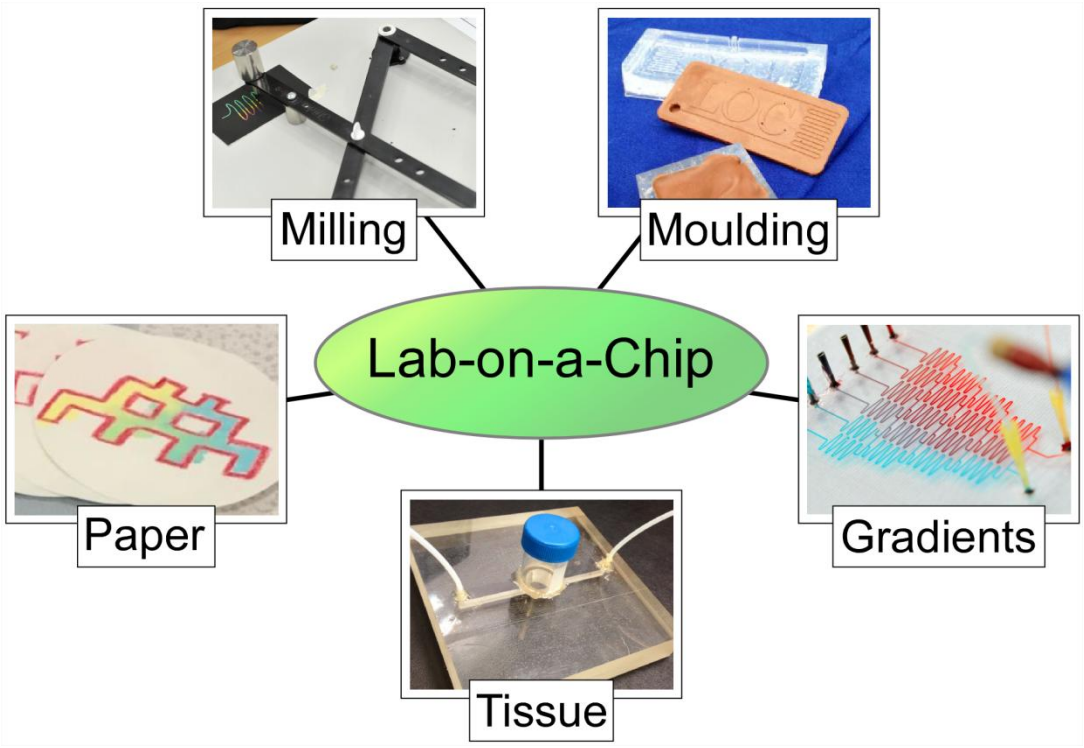


FIG. 1. Five lab-on-a-chip based activities designed for school students and the general public.

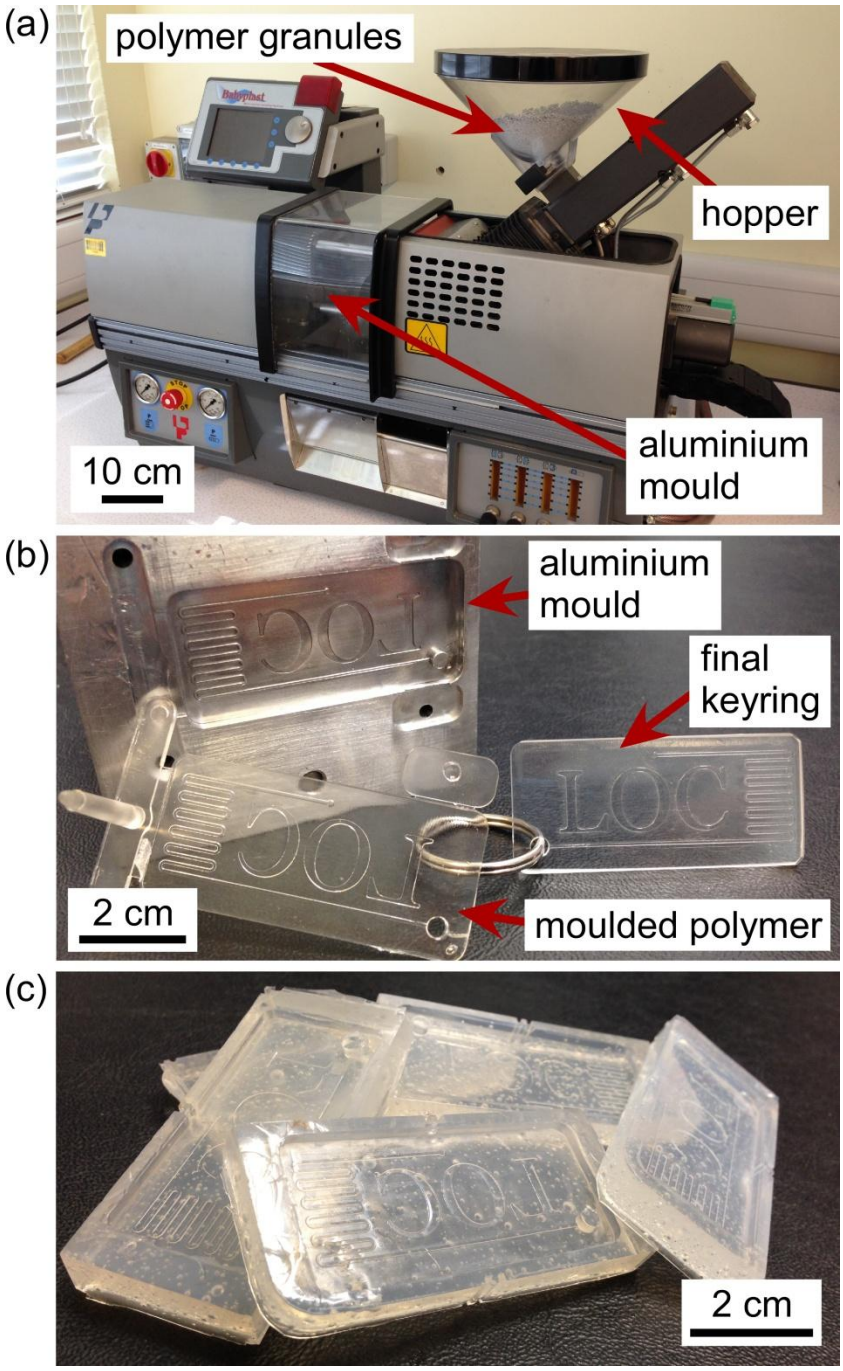


FIG. 2. (a) Polymer microinjection moulder used to fabricate PMMA keyrings. (b) The aluminium mould and the PMMA devices formed from it. (c) Food-grade silicone moulds fabricated from the PMMA keyrings.

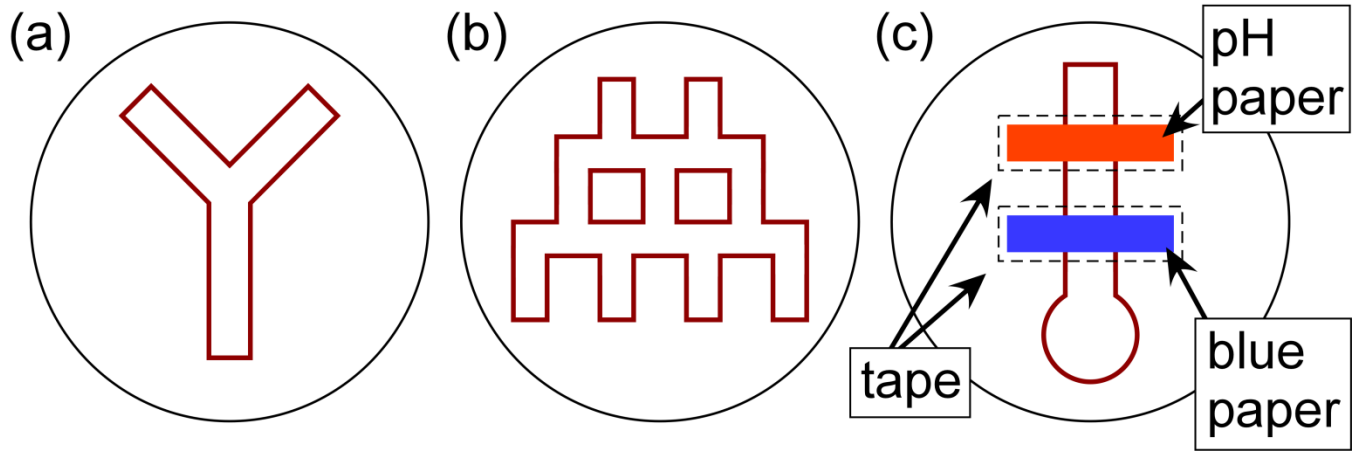


FIG. 3. Wax designs for paper devices: (a) Y-shaped channel, (b) gradient channel design, (c) laminar flow assay design.

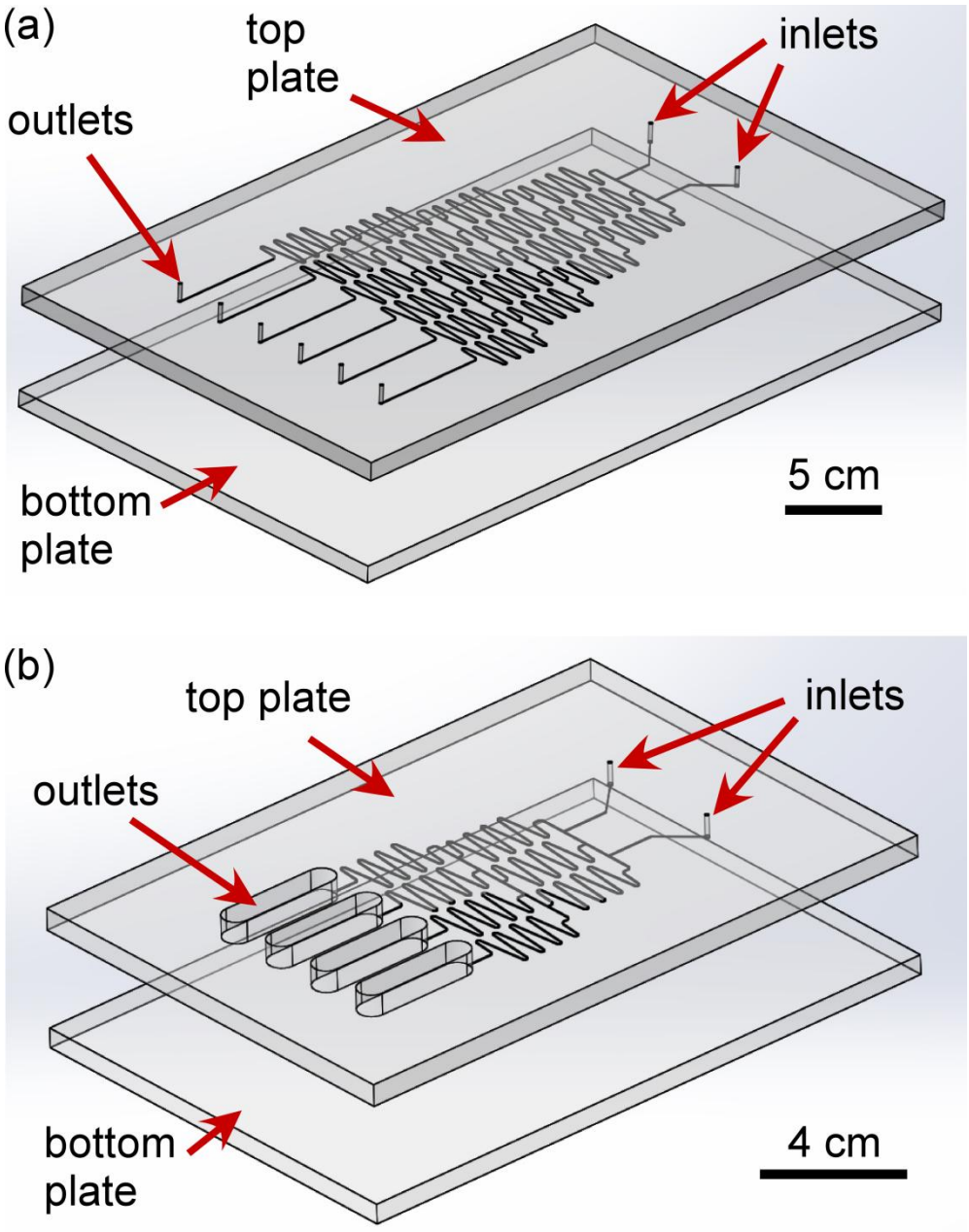


FIG. 4. Exploded SolidWorks designs for CNC milling of oversized gradient devices. (a) Design 1, used as a "demo chip", featuring four levels of branching and six outlets. (b) Design 2, referred to as the "juice chip", which consisted of two levels of branching and four outlets.

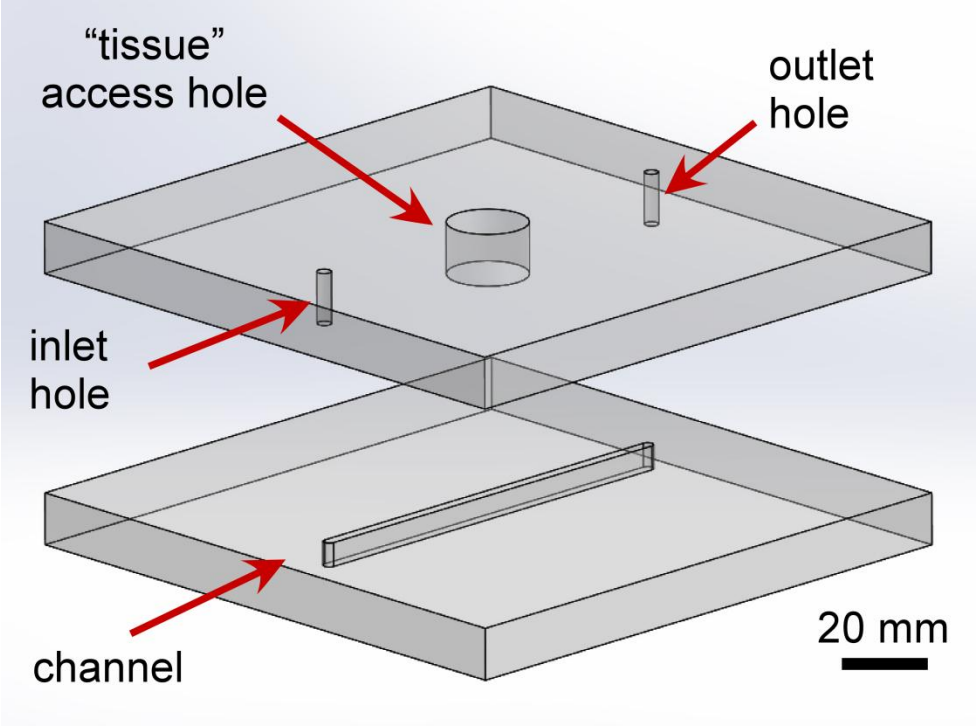


FIG. 5. SolidWorks design for CNC milling of an oversized tissue analysis chip. The top plate featured access holes, while the bottom plate featured a channel.

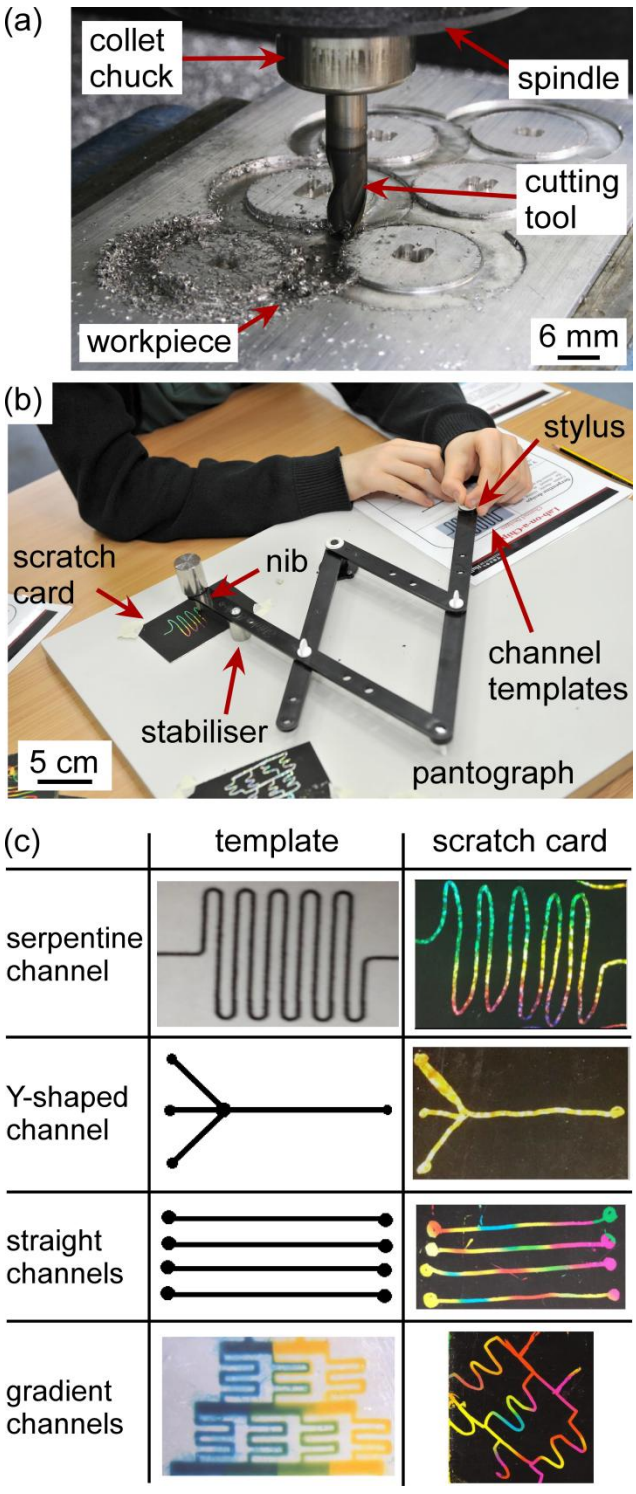


FIG. 6. (a) Photograph of a tool cutting a design into a metal workpiece. The example shown would then be taken for use as a master for injection moulding, (b) Pantograph being used by a student to etch a channel design from a template into a scratch art card. (c) The channel designs on the template and the resultant designs transferred to the scratch art cards.

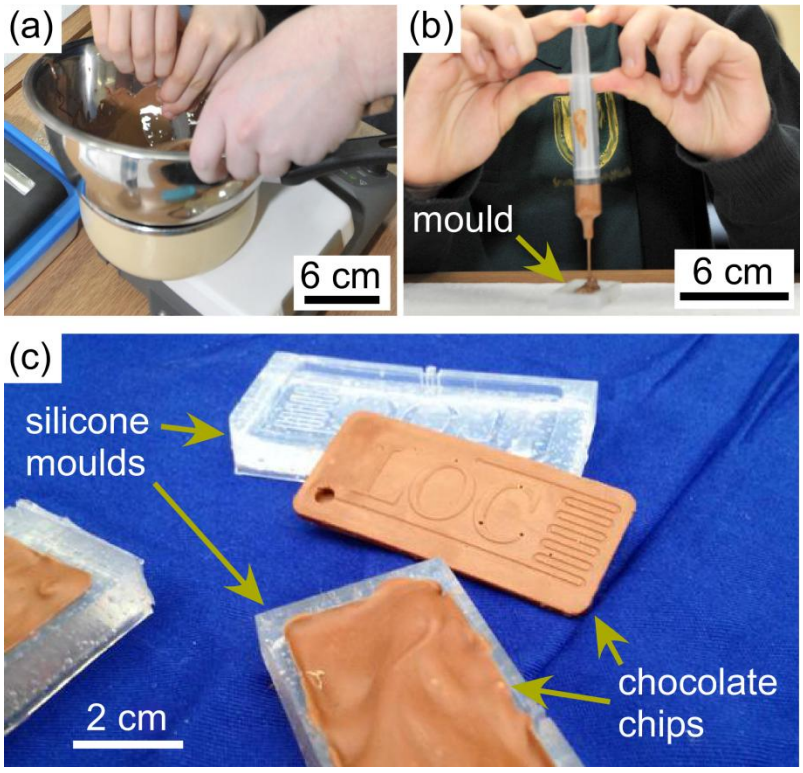


FIG. 7. Moulding of chocolate microfluidic chips. (a) A student extracting molten chocolate into a 10 mL syringe from an improvised bain-marie. (b) The student dispensing molten chocolate into a silicone mould. (c) Cooled chocolate LOC devices and their moulds.

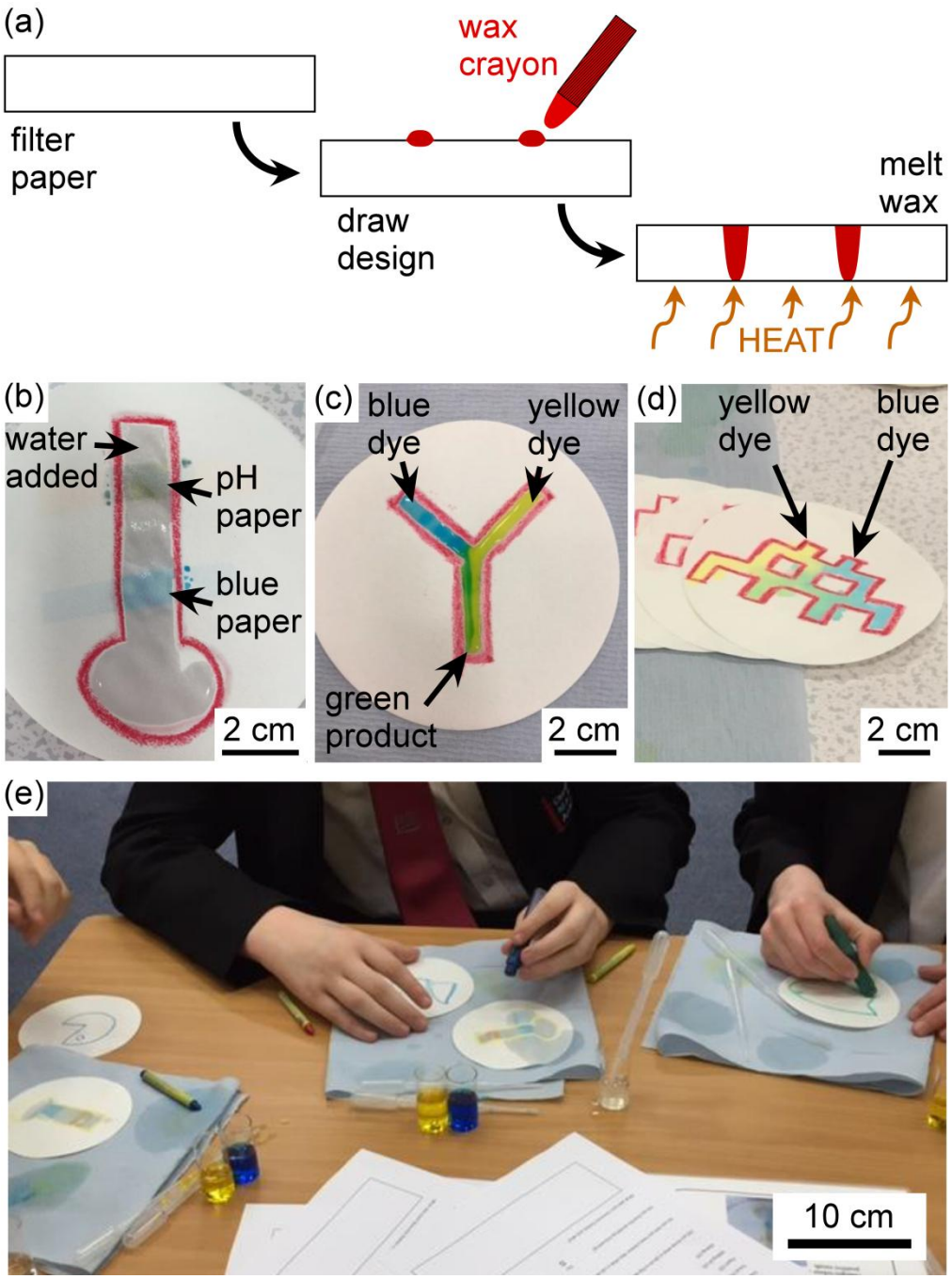


FIG. 8. (a) Preparation of paper microfluidic devices for the workshop by melting wax into the paper. (b) Laminar flow style device. (c) Y-shaped channel. (d) Gradient channel design. (e) Students preparing their own paper designs.

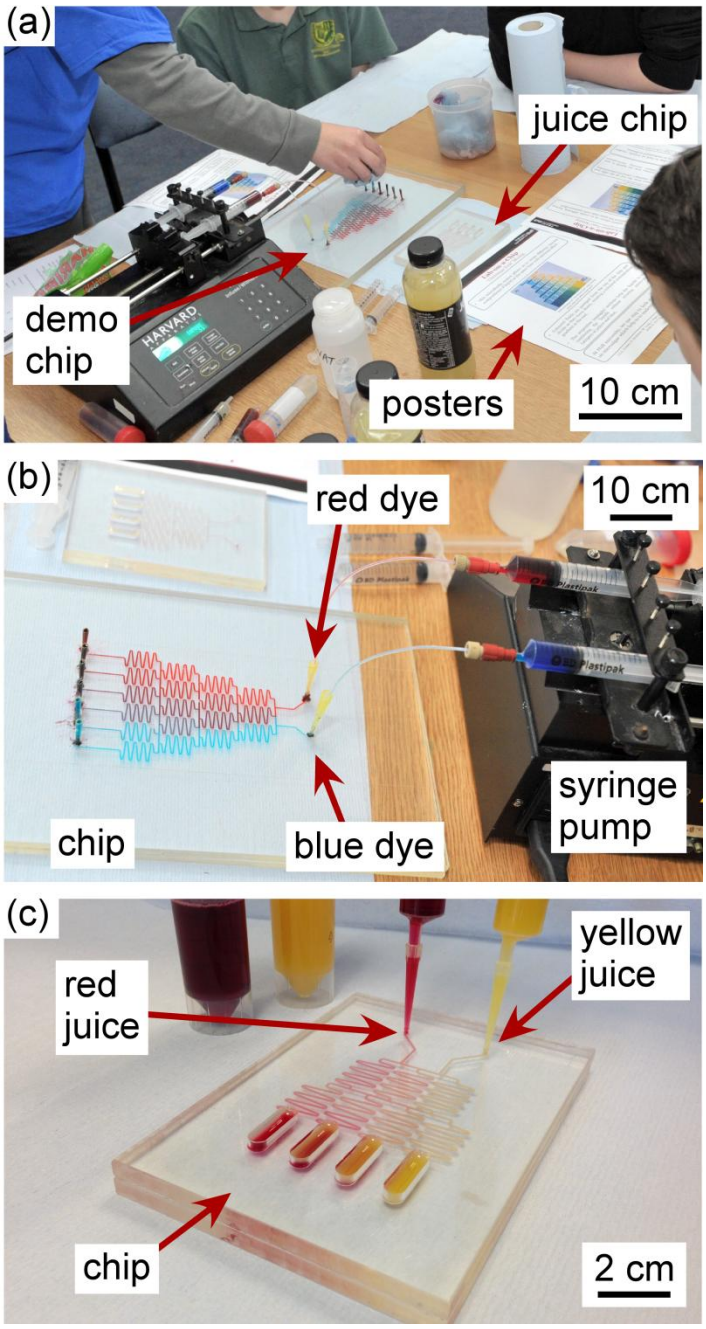


FIG. 9. (a) Demonstration of gradient formation microfluidic devices to schoolchildren, using a demo chip and a juice chip. (b) Continuously flowing red and blue food dye solutions pumped through the oversized demo chip to show the principle to schoolchildren. (b) An oversized juice chip, with syringes of fruit juices connected for students to try to manually generate their own gradient across the chip.

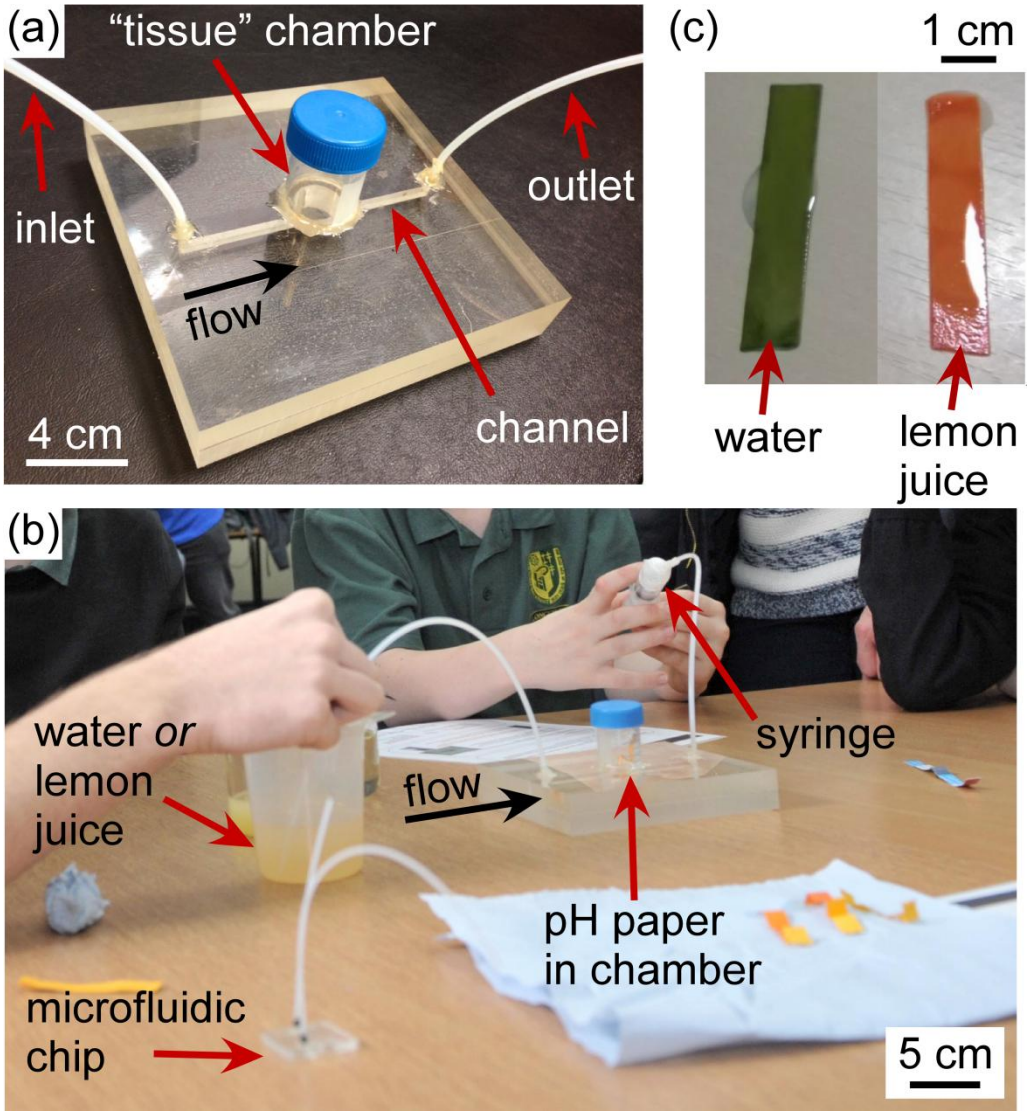


FIG. 10. (a) Oversized tissue chip featuring a chamber into which pH paper was added to mimic a tissue sample. (b) Students manually operating the device by drawing either lemon juice or water through the channel by negative pressure, exposing the pH paper "tissue" to different "drugs". (c) Effect of water and lemon juice on the pH paper, indicating positive and negative effects of the "drugs". An actual tissue microfluidic device was also shown to students to demonstrate the features of the real device compared to the oversized demonstration device.

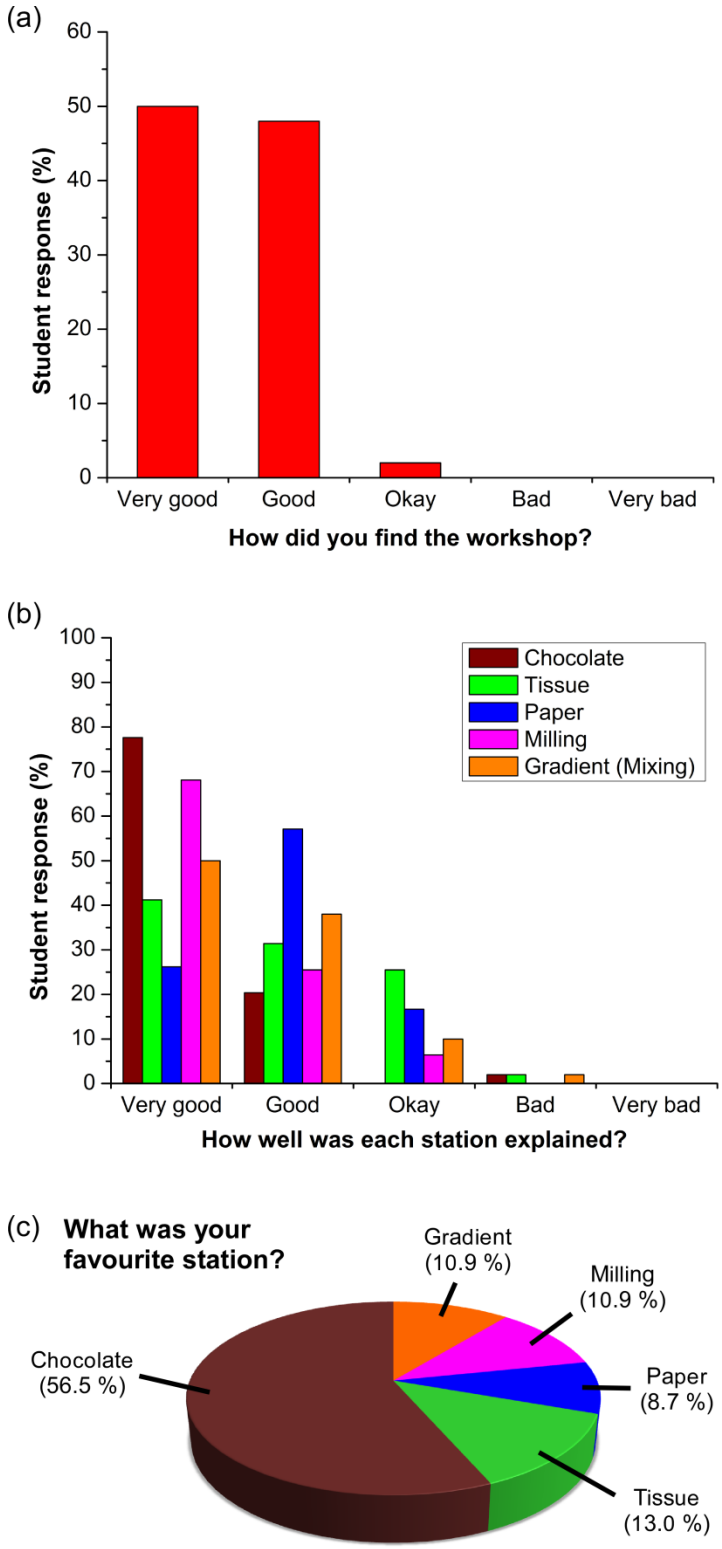


FIG. 11. Student responses to the questionnaire. (a) “How did you find the workshop?”. (b) “How well was each station explained?”. (c) “What was your favourite station?”.

SUPPLEMENTAL MATERIAL

Lab-on-a-chip workshop activities for secondary school students

Mohammad M. N. Esfahani,[1,2] Mark D. Tarn,[1] Tahmina A. Choudhury,[1] Laura C. Hewitt,[1] Ashley J. Mayo,[1] Theodore A. Rubin,[1] Mathew R. Waller,[1] Martin G. Christensen,[1] Amy Dawson,[3] Nicole Pamme[1]

[1]*Department of Chemistry, University of Hull, Cottingham Road, Hull, HU6 7RX, UK*

[2]*School of Engineering, University of Hull, Cottingham Road, Hull, HU6 7RX, UK*

[3]*School of Biological, Biomedical and Environmental Sciences, University of Hull, Cottingham Road, Hull, HU6 7RX, UK*

CONTENTS

- Questionnaire form *Page S2*
- Questionnaire results **(TABLES S1-S3)** *Page S3*
- Posters **(TABLE S4, FIGS. S1-S6)** *Page S4*

QUESTIONNAIRE FORM

Lab on a chip workshop questionnaire

The following questions will be used as feedback on the lab on a chip workshop and will be used as part of a third year chemistry project on the introducing of lab on a chip to the public. The questionnaire results are anonymous, Thank you for your help.

Choose **one** of the following that best describes your experience in the work shop today.

How did you find the workshop?	Very good	Good	Ok	Bad	Very bad
	☐	☐	☐	☐	☐

How well was the each station explained?	Very good	Good	Ok	Bad	Very bad
Chocolate LOC	☐	☐	☐	☐	☐
Tissue LOC	☐	☐	☐	☐	☐
Paper LOC	☐	☐	☐	☐	☐
Milling of LOC	☐	☐	☐	☐	☐
Mixing LOC	☐	☐	☐	☐	☐

Did you know what a Lab on a chip was before today?	Yes	No
	☐	☐

Do you feel you have a better idea what a Lab on a chip is now?	Yes	No
	☐	☐

Did you find the workshop interesting?	Yes	No
	☐	☐

What was your favourite Station and why?

QUESTIONNAIRE RESULTS

Questionnaire forms (see previous section) were collected from 51 students during the workshop. The relevant data is shown graphically in the main manuscript, while the tables below (TABLES S1-S3) show the raw data obtained from the forms. Note that some forms were partially incomplete, and such instances are shown here in the "*No answer*" column.

TABLE S1. Assessment of each student's response to the workshop overall, and to the individual activities. "Mixing LOC" refers to the gradient formation activity.

	Very good	**Good**	**OK**	**Bad**	**Very bad**	**No answer**
How did you find the workshop?	25	24	1	0	0	1
How well was each station explained?						
Chocolate LOC	38	10	0	1	0	2
Tissue LOC	21	16	13	1	0	0
Paper LOC	11	24	7	0	0	9
Milling of LOC	32	12	3	0	0	4
Mixing LOC	25	19	5	1	0	1

TABLE S2. Determination of the students' knowledge of microfluidics before and after attending the workshop, and whether they found it interesting.

	Yes	**No**	**No answer**
Did you know what LOC was before today	0	51	0
Do you feel you have a better idea of what LOC is now?	46	3	2
Did you find the workshop interesting?	50	0	1

TABLE S3. Evaluating the popularity of each workstation.

	Chocolate	**Tissue**	**Paper**	**Milling**	**Mixing**	**No answer**
What was your favourite station?	26	6	4	5	5	5

POSTERS

Posters were printed out (A4 size) multiple times for each activity and distributed around the relevant workstation. The posters were designed by the undergraduate project students to give the secondary school students background information on the real techniques employed in microfluidics, and to then relate the technique to the workshop activity that was being performed at the workstation. TABLE S4 details each poster and its purpose.

TABLE S4. List of the posters used in the workshop and a brief description of the purpose of each one.

Activity / workstation	Poster	Description of poster
CNC milling / pantograph	**Poster 1a**	A choice of four microfluidic chip designs are offered for students to trace their designs from, simply by aligning the stylus at a suitable starting point.
	Poster 1b	Describes the CNC milling process and the typical instrumentation involved. The pantograph method of sketching from an original image is then related to this milling process.
Chocolate injection moulding	**Poster 2**	The process of injection moulding is described, and related to the moulding of a chocolate device in a silicone mould.
Paper microfluidics	**Poster 3**	Brief explanation of how paper microfluidics are prepared and how they operate, with some applications given.
Gradient formation	**Poster 4**	Explanation of how a gradient of two fluids can be formed in a chamber via diffusional mixing between consecutively split streams.
Tissue-on-chip	**Poster 5**	Example of how microfluidics can be used for cancer targeted therapy, with a comparison between conventional and microfluidic methods.

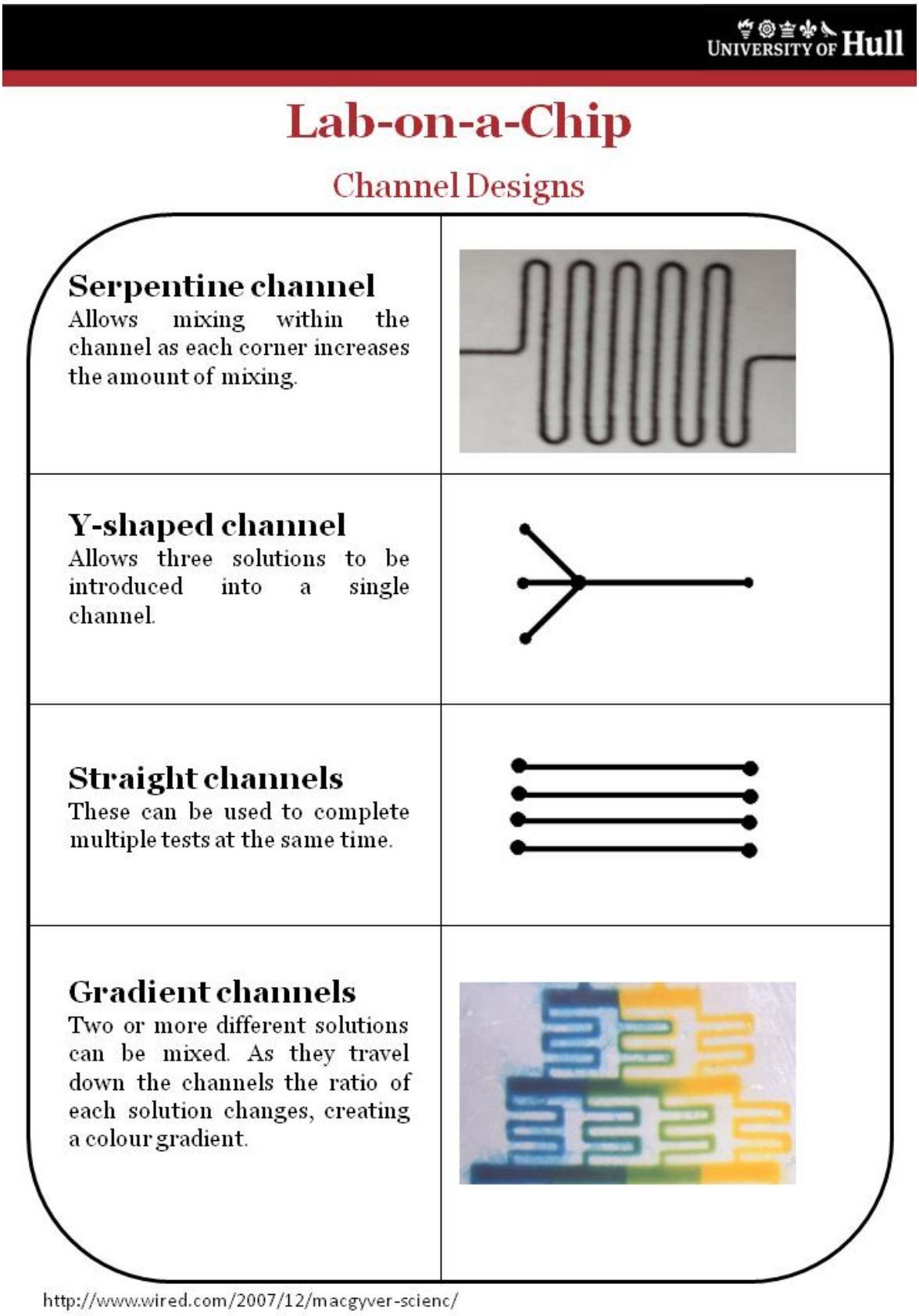


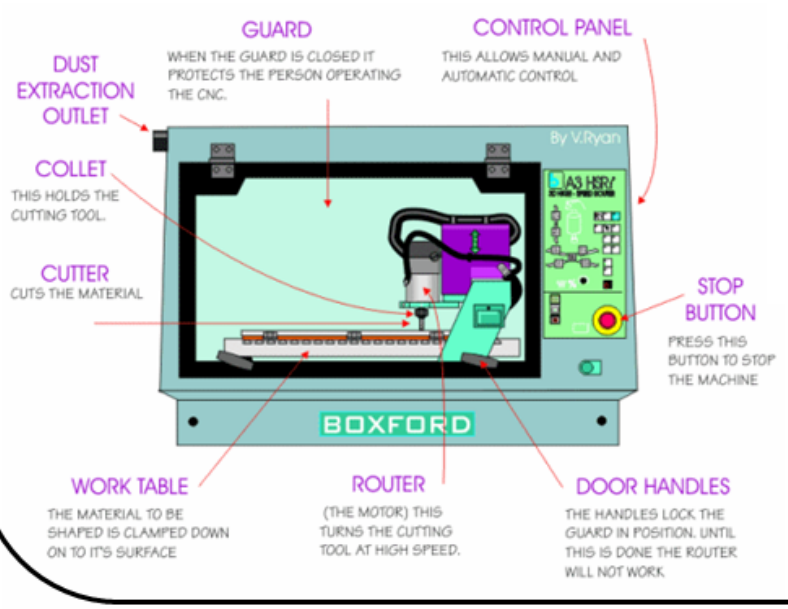
FIG. S1. Poster 1a, which provided template chip designs for use with the pantograph.

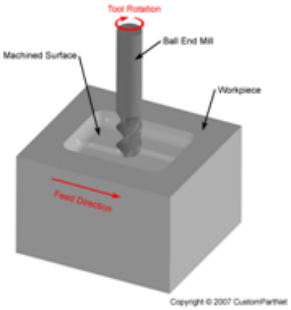
UNIVERSITY OF Hull

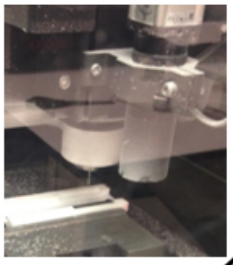
Lab-on-a-Chip

Milling

A computer numerically controlled (CNC) milling machine can be used to take a shape that has been drawn on a computer and cut it out of a material using a "cutting tool". A chip can be made by milling it directly out of a material, or by milling out a mould for injection moulding of plastic chips.

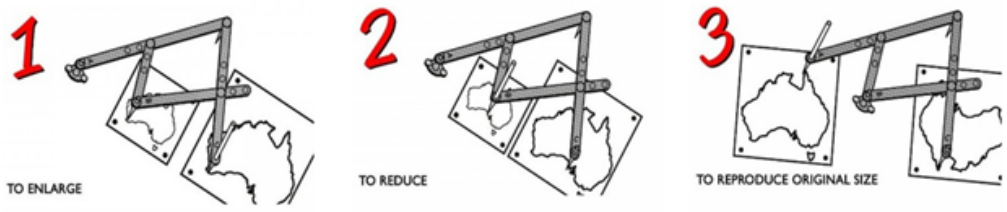






Pantograph

The pantograph shows how a CNC milling machine works. By tracing a chip design using the pantograph you are mimicking how a computer traces an image to mill and the scratcher represents the tool doing the milling. It shows how the image is always kept in proportion and the scale can change depending on the settings.



http://arabtraining.net/vb/t49772.html, http://www.custompartnet.com/glossary/e

FIG. S2. Poster 1b, showing the concepts of CNC milling and the pantograph.

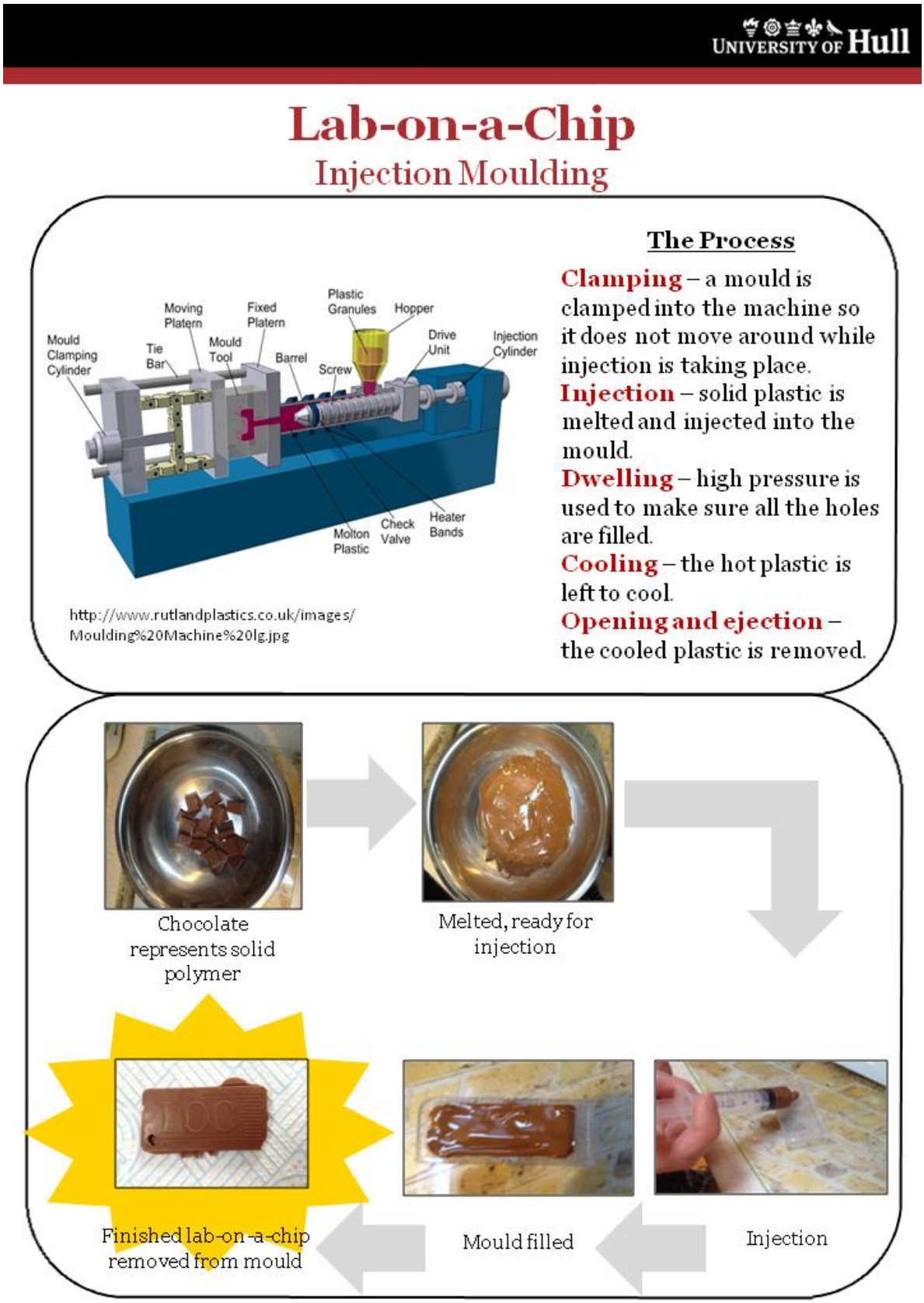


FIG. S3. Poster 2, showing polymer injection moulding and the chocolate counterpart.

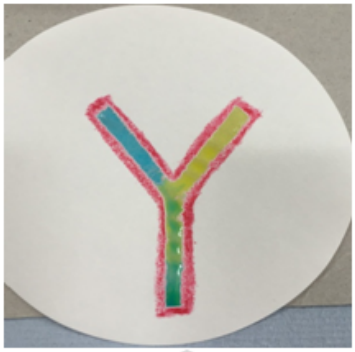
UNIVERSITY OF Hull

Lab-on-a-Chip

Paper Microfluidics

What is Paper Microfluidics?

- Not all microfluidic device have to be made from glass, some can be as simple as a piece of paper.
- The natural capillary channels within paper make it easy for fluids to absorb and travel through the material.
- A barrier can be added to the paper, controlling the fluids movements and confining it within a channel.



Demonstration of how fluids flow through the capillary channels in paper

Applications

- Paper microfluidics have a wide application in the medicinal industry.
- Common household tests that take advantage of this technology include:
  - Urine dipstick tests for glucose in diabetics.
  - Home pregnancy testing; a protein added to the paper changes colour when detected in the urine, giving a positive result.

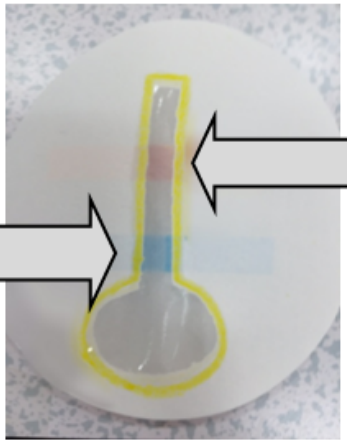


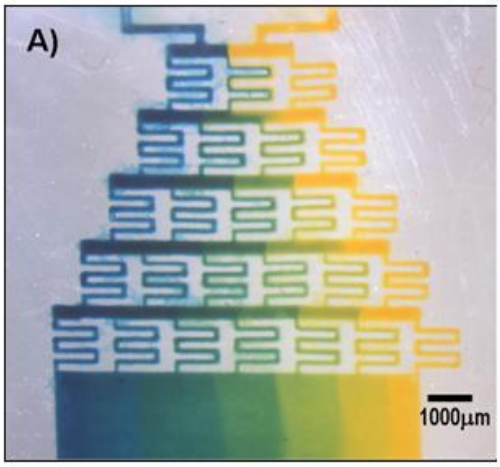
FIG. S4. Poster 3, demonstrating the properties and uses of paper microfluidics.

UNIVERSITY OF Hull

Lab-on-a-Chip

"Christmas Tree" Mixing

- This microfluidic system allows us to create different but controlled compositions of liquid at the same time with minimal effort.



Demonstration of "Christmas tree" chip mixing using blue and yellow food dye [1]

- Coloured fluids are pumped from one end of the chip and divide as they move down, creating a coloured concentration gradient at the end.
- The serpentine (squiggly) sections help the liquids to mix, combining the liquids without creating micro-phases (stripes) of yellow and blue.

At Hull University, we use gradient chips for toxicity studies on microalgae, to help us to understand pollution.

[1] A. Grimes, D. Breslauer, M. Long, J. Pegan, L. Lee, M. Khine, *Lab Chip*, 2008, **8**, 170-172.

FIG. S5. Poster 4, showing the generation of a gradient by stream splitting and diffusion.

UNIVERSITY OF Hull

Lab-on-a-Chip

Tissue on a Chip

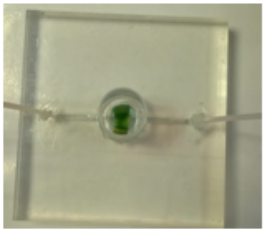
Cancer Targeted Therapy

- As one of the most common diseases with many different varieties, cancer requires many different treatment options.
- Lab-on-a-chip devices can be used to improve the effectiveness of cancer treatments.
- Targeted therapy is used to determine which type of cancer is present and therefore which drugs can help to combat the cancer the best.

Demonstration

This demonstration uses a simplified and large scale version of the lab-on-a-chip "tumour chip" to show how the process works.

The chip contains a single channel with an entry and exit, and a large chamber in the centre where the tissue sits and the reaction takes place. A solution is passed through the channel and into the chamber, before exiting the chip.



The colour change indicates which type of cancer is present and therefore which type of treatment is required for the patient.

Green indicates that traditional treatments are required, chemotherapy etc.
Red results shows that an alternate treatment would be more effective.

Conventional method	Vs.	Lab-on-a-Chip method
Slow response (24 hours+)		Fast response (2 hours)
Expensive		Relatively cheap
Requires highly trained technicians		Easy to use
Surgery required		No surgery required

Which one would you pick?

FIG. S6. Poster 5, demonstrating the use of microfluidics for cancer therapy research.