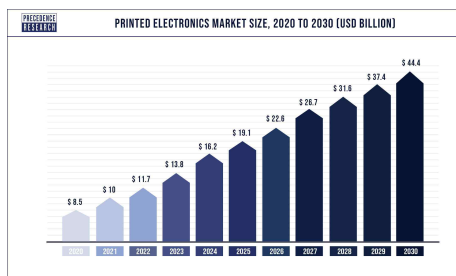
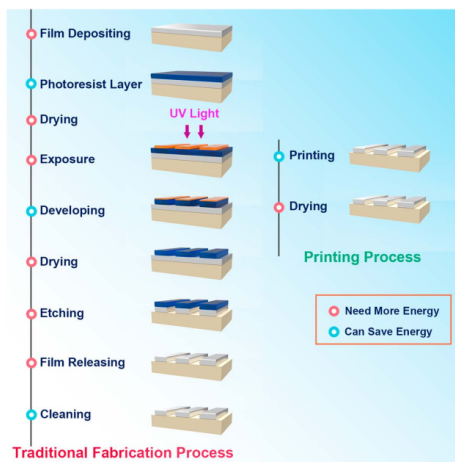



Intro to printing

Printed electronics refers to very thin electronic devices and circuits that are produced by the application of inks with desired electric properties to various substrates. They can be manufactured in volume for a much lower cost compared to other electronics with methods common in the printing industry. This makes them particularly well-suited for applications where the benefits of electronic functionality alone do not outweigh the associated expenses. Additionally they can offer flexible form factors and the ability of large area coverage. Another benefit that may come from their spread is to lessen the impact of e-waste, since printed electronics can be much less toxic for the environment and more easily recyclable than the rest, or even biodegradable. They cannot compete with silicon electronics in performance due to the large resistance of conductive inks, the lack of support for high frequency and the high variability in manufacturing. While the ability to cover large areas is sometimes desirable, a lot of applications demand miniaturization that they cannot offer. A variety of active and passive devices, including transistors, resistors, capacitors, sensors, harvesters and antennas can be implemented with them. They are thought to be an emerging market with considerable potential to broaden the role of computation in everyday living. They can help the pervasiveness of the Internet-of-Things reach far deeper, and thus synergize well with other advances in the sector. A recent report by IDTechEx[money] forecasts the global market for printed flexible electronics, excluding OLEDs, to reach 12 billion dollars by 2033.

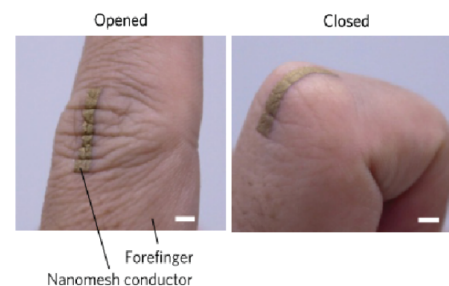
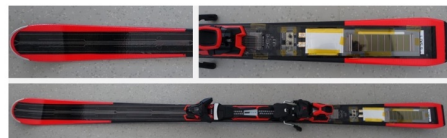


Uses of printed electronics

The usage of printed electronics most people may be familiar with in their everyday lives is the membrane used to detect key presses in most non-mechanical keyboards, or perhaps windshield defrosters.  Other usages include:

- **Sensors:** flexible, biodegradable and stretchable sensing elements enable the efficient monitoring of many processes. A variety of properties of the world can be measured by printed sensors, including temperature, touch, strain, gasses, humidity, light levels and presence of certain chemicals.[CHEMICALS] The flexibility and non-toxicity is especially relevant for medical monitoring, so biosensors have received a lot of attention, with some (for example ,printed seizure detecting patches) already commercially available.
- **RFID:** RFID (Radio Frequency Identification) is a wireless technology reader, enabling seamless object identification and tracking through unique identification codes stored in the tags. The goal of printed RFID is to replace current methods for identifying goods with smart labels. RFID tags are usually passive and don't require a power supply. They can be cheaply made with any common printing method. They have been shown to operate on 5G and WLAN frequencies, and can even have sensor capabilities. Currently mostly used in ticket fares and anti-shoplifting.
- **Energy harvesting:** Printed batteries can only provide power to the functional parts of printed circuits for a limited time, and can take up a significant portion of the circuit's area. In order to enable greater autonomy to deployed printed electronics the ability to harvest energy from the environment is crucial. Printed harvesters can draw power from radio signals, vibrations and most commonly, light. Printed photoelectric/solar cells have also drawn a lot of interest outside the realm of harvesters for small circuits, since while their performance doesn't reach the levels of rigid silicon solar cells they can be deployed in a wider selection of spaces, including wearables.
- **Lighting:** LEDs have become the predominant light source, in place of the energy wasteful incandescent lamps and the environmental minefields of fluorescent lighting. OLEDs further increase the energy savings and produce softer and more uniform lighting. Printing seems like a promising solution for low cost manufacturing of OLEDs with competitive luminous efficiency and enable them to cover large areas. Paper thin light panels have been demonstrated that way.

- Displays: Displays are one of the more mature aspects of printed electronics, with large 4K printed OLED displays are commercially available. They enable flexible displays, that have many applications in consumer electronics and wearables and thus are a 5 billion dollar market. Even if the flexible display is not fully printed, printed electronics can offer it additional features. QLED displays may also one day be printed if printing accuracy keeps increasing.
- Wearables: Wearable electronic devices are already very popular, such as smart watches or hearing aids, or NFC rings. Printed electronics have much to offer to the space thanks to their flexibility. Conductive materials have been developed that can be printed on fabric and withstand washing with detergent, allowing electronics to be embedded in regular pieces of clothing. Printed sensors can be used for activity tracking, one of the most popular features of today's smartwatches, or health monitoring, with printed patches for seizure detection already on the market. One can also imagine they would be of interest to the fashion industry.
- Transistors: [WHY IS EGFET NMOS HOW DOES IT COMPARE]



Manufacturing methods

Printed electronics are manufactured using techniques from the graphic print industry. They are split into contact or R2R printing techniques that use a template and contactless that don't. Multiple printing steps are required for the multiple layers of the circuit. Contact printing techniques include:

- Gravure: In gravure, the printing cylinder gets engraved with the template and is partly submerged in ink during the process, with a blade discarding excess ink. This only leaves ink in the template parts, which is transferred to the substrate under pressure. Gravure can print in high resolution and speed compared to other methods, but the cost of engraving the cylinder makes it only useful for very large batches.
- Offset: In offset printing the shape of the template is deposited on a cylinder with an ink accepting substance and the negative of the template is covered with ink repelling substances. That way only the shape of the template absorbs ink from an ink roller, and then gets transferred onto the substrate via an intermediate cylinder.
- Flexography: The template is embedded onto a flexible plate that is wrapped around a printing cylinder such that parts of the shape raised. Ink applied to this cylinder only gets transferred to a second cylinder, and then the substrate, if it is on the raised parts that correspond to the template. It can support both non-porous and porous substrates.
- Screen printing: A "screen" in this case is a close-knit fabric, such that ink can pass through only by applying pressure. A stencil of the template is placed on top of the screen and a blade pushes ink through the uncovered parts onto the substrate. Screen printing is the simplest technique of the bunch and can create thicker layers and print on curved surfaces. It suffers from lower resolution compared to other methods.
- Pad printing: Ink gets onto an engraving of the template. A soft pad is then pressed on it and transfers the ink with the desired shape to the substrate. It can print on surfaces of 3D objects.

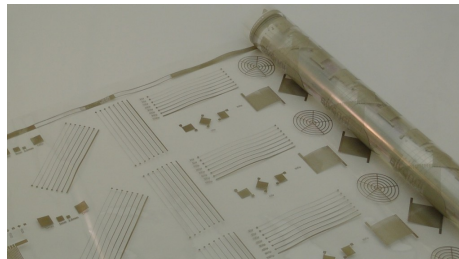
Contactless techniques include:

- Inkjet: Ink is dropped onto the substrate from tiny spouts. Either there are enough spouts to cover the width of the print or they can be moved around to do so. It does not require large equipment and different designs can be printed in high resolution without complications in changing templates, making it ideal for

printing on demand. It's main drawback is it's printing speed. Continuous stream inkjet has a stream of ink be directed onto the substrate or to a trash bin depending on design information. It is can print larger batches than Drop-on-Demand inkjet, but with five times lower resolution. DoD controls whether ink will flow using a valve, so ink is not wasted. It is deployed at smaller scales than Continuous stream.

- Aerosol: The ink is atomised into a fine mist via compressed air or ultrasound, accelerated and sprayed onto the substrate. It can be used on curved surfaces and can provide even smaller feature sizes than inkjet, but is prohibitively slow.

Additionally methods like vacuum deposition, in which evaporated ink coats a surface in a vacuum, or dip pen nanolithography, in which an atomic force microscope applies the ink very precisely on the substrate, are sometimes considered included in the printed electronics umbrella, and although they can achieve smaller feature sizes they require specialised equipment and are not as cost friendly as the traditional printing methods and thus less relevant.



Inks

In order to implement functional circuits inks with conducting, semi-conducting and dielectric properties are needed. They usually consist of nanoparticles of materials with these properties mixed with solvent to the desired viscosity and other additives to enable the printing process. Both organic and inorganic materials can be used.

- Conducting inks: The majority of materials for conducting inks are metal nanoparticles, the most common being silver. Although silver is in the category of precious metals silver ink is not awfully expensive, with pens of conductive silver ink going for less than 4 dollars. Other metals used are gold, aluminum and copper. Copper and aluminum inks suffer much worse ageing than silver ones. Organic inks are often based on carbon nanotubes or graphene. Cheaper polymers are also used, despite their inferior conductivity. The most popular is PEDOT:PSS. Ceramic materials are also used in conducting inks, mainly indium tin oxide(ITO), although it is an expensive material.
- Semiconducting inks: The most common inorganic materials used are silicon and germanium and of the organic ones most are again CNT or graphene based. Both p-type and n-type materials can be produced from those, although p-types have historically been much higher performing. (The opposite holds true for electrolyte gated transistors.)
- Dielectric inks: The dielectric layer needs to be thicker than the conducting and semiconducting layers in order for charge not to leak through it. Substrate materials, ceramic oxides and polymers can be used as the active ingredient.



Machine learning in printed circuits

- Tahoori et al [x14] demonstrates an analog two input neuron, and shows how it could be expanded to fully printed analog neural networks with MAC and activation operations.
- Douthwaite et al [x15] Uses time domain encoding of signals, representing magnitude as pulse width and encoding weights with current mirrors. Accumulation is done by linearly charging a capacitor with the mirrored pulses.
- Gkoupidenis et al [x16] mimic biologically inspired synaptic functions with electrolyte-gated transistors and show how they could be used for a single layer perceptron.
- Ozer et al [x17] envision what an automatic process for creating bespoke processors for a variety of ML architectures in printed electronics could look like, but don't go beyond the vision stage.
- Bleier et al [x18] present a printed microprocessor with an instruction set customised to the program at hand.
- Weller et al [x19] leverage stochastic computing to reduce the requirements of mixed analog - digital neural networks but with heavy accuracy cost.
- Mubarik et al [x20] evaluate small machine learning architectures (decision trees, random forests and support vector machines) in digital, lookup table based and analog architectures in bespoke printed circuits.
- Armeniakos et al [x21] expand to more demanding SVMs and Multi Layer Perceptrons, and provide a method to shift the weight coefficients of the networks to more hardware friendly values and apply circuit level netlist pruning to reduce area and power to more acceptable values.

Datasets

The datasets chosen to train models for and implement are the ones used by [x20] and [prof]. That way results for model accuracy and area / power requirements can be compared with other approaches in the literature. Like in those papers, categorical features were removed from the datasets, leaving only inputs from sensors, since they are all the actual printed system would have access to (this assumption may be circumvented, but this is beyond the current scope). Note that the feature selection may not be the same as the prior papers, since the pieces of data they kept were not documented. All of them were taken from the UCI machine learning repository[x7]. A short description of the datasets:

- Arrhythmia[x8]: Diagnosis of cardiac arrhythmia from 12 lead ECG recordings.
- Cardiotocography[x9]: Diagnosing problems in the heartrate of unborn infants.
- Pendigits[x10]: Classification of written digit from a series of 8 pressure signals from touch sensors.
- Human activity recognition(HAR)[x11]: Classification of the type of movement a person is making(standing, climbing stairs etc) using accelerometers from cellphones on their waists.
- Gas Identification[x12]: Classification of gas presence using chemical sensors.
- Wine Quality(White wines)[x13]: Estimating the percieved enjoyment of various white wines based on acidity and mineral traces.
- Wine Quality(Red wines)[x13]: Equivelant to the above for red wines.

The datasets use inputs from sensors that at least approximately correspond to ones that have been demonstrated possible to manufacture by printing. The complete system including both sensors, classifier and power supply could thus somewhat realistically be physically implemented, and not be very far from an actual usecase of the technology.

Sensor	Dataset
Electrocardiography sensor on paper[x1]	Arrythmia
Electrocardiography sensor on paper[x1]	Cardio
Printed movement sensor	Human activity recognition
Printed gas sensor[x6]	Gas identification
Printed piezoelectric sensor[x4]	Pendigits
Printed pH sensor[x2], Inkjet mineral sensor[x3]	Wine Quality(White)
Printed pH sensor[x2], Inkjet mineral sensor[x3]	Wine Quality(Red)

- [x1] Eloïse Bihar, Timothée Roberts, Mohamed Saadaoui, Thierry Hervé, Jozina B. De Graaf, George G. Malliaras, Inkjet-Printed PEDOT:PSS Electrodes on Paper for Electrocardiography, *Advanced Healthcare Materials* Volume 6, Issue 6
- [x2] Jose, M., Mylavarapu, S. K., Bikkarolla, S. K., Machiels, J., KJ, S., McLaughlin, J., ... & Deferme, W. (2022). Printed pH Sensors for Textile-Based Wearables: A Conceptual and Experimental Study on Materials, Deposition Technology, and Sensing Principles. *Advanced Engineering Materials*, 24(5), 2101087.
- [x3] Jelbuldina, M., Younes, H., Saadat, I., Tizani, L., Sofela, S., & Al Ghaferi, A. (2017). Fabrication and design of CNTs inkjet-printed based micro FET sensor for sodium chloride scale detection in oil field. *Sensors and Actuators A: Physical*, 263, 349-356.
- [x4] Tuukkanen, S., & Rajala, S. (2015, November). A survey of printable piezoelectric sensors. In *2015 IEEE SENSORS* (pp. 1-4). IEEE.
- [x5] Yamamoto, Y., Harada, S., Yamamoto, D., Honda, W., Arie, T., Akita, S., & Takei, K. (2016). Printed multifunctional flexible device with an integrated motion sensor for health care monitoring. *Science advances*, 2(11), e1601473.
- [x6] Dai, J., Ogbeide, O., Macadam, N., Sun, Q., Yu, W., Li, Y., ... & Huang, W. (2020). Printed gas sensors. *Chemical Society Reviews*, 49(6), 1756-1789.
- [x7] D. Dua and C. Graff, "UCI machine learning repository," 2017. [Online]. Available: <http://archive.ics.uci.edu/ml>
- [x8] Guvenir, H. A., Acar, B., Demiroz, G., & Cekin, A. (1997, September). A supervised machine learning algorithm for arrhythmia analysis. In *Computers in Cardiology 1997* (pp. 433-436). IEEE.
- [x9] D. Ayres-de Campos, J. Bernardes, A. Garrido, J. Marques-de Sa, and L. Pereira-Leite, "Sisporto 2.0: a program for automated analysis of cardiotocograms," *Journal of Maternal-Fetal Medicine*, vol. 9, no. 5, pp. 311-318, 2000.
- [x10] F. Alimoglu and E. Alpaydin, "Methods of combining multiple classifiers based on different representations for pen-based handwritten digit recognition," in *Proceedings of the Fifth Turkish Artificial Intelligence and Artificial Neural Networks Symposium (TAINN 96)*. Cite-seer, 1996.
- [x11] D. Anguita, A. Ghio, L. Oneto, X. Parra, and J. L. Reyes-Ortiz, "A public domain dataset for human activity recognition using smartphones." in *Esann*, 2013.
- [x12] S. Feng, F. Farha, Q. Li, Y. Wan, Y. Xu, T. Zhang, and H. Ning,

“Review on smart gas sensing technology,” *Sensors*, vol. 19, no. 17, p. 3760, 2019.

[x13] P. Cortez, A. Cerdeira, F. Almeida, T. Matos, and J. Reis, “Modeling wine preferences by data mining from physicochemical properties,” *Decision Support Systems*, vol. 47, no. 4, pp. 547–553, 2009.

[x14] D. D. Weller, M. Hefenbrock, M. B. Tahoori, J. Aghassi-Hagmann, and M. Beigl, “Programmable neuromorphic circuit based on printed electrolyte-gated transistors,” in *2020 25th Asia and South Pacific Design Automation Conference (ASP-DAC)*, 2020, pp. 446–451.

[x15] Douthwaite, M., García-Redondo, F., Georgiou, P., & Das, S. (2019, October). A time-domain current-mode mac engine for analogue neural networks in flexible electronics. In *2019 IEEE Biomedical Circuits and Systems Conference (BioCAS)* (pp. 1–4). IEEE.

[x16] H. Ling, D. A. Koutsouras, S. Kazemzadeh, Y. van de Burgt, F. Yan, and P. Gkoupidenis, “Electrolyte-gated transistors for synaptic electronics, neuromorphic computing, and adaptable biointerfacing,” *Applied Physics Reviews*, vol. 7, no. 1, p. 011307, 2020.

[x17] Ozer, E., Kufel, J., Biggs, J., Brown, G., Myers, J., Rana, A., ... & Ramsdale, C. (2019, July). Bespoke machine learning processor development framework on flexible substrates. In *2019 IEEE international conference on flexible and printable sensors and systems (FLEPS)* (pp. 1–3). IEEE.

[x18] Bleier, N., Mubarik, M. H., Rasheed, F., Aghassi-Hagmann, J., Tahoori, M. B., & Kumar, R. (2020, May). Printed microprocessors. In *2020 ACM/IEEE 47th Annual International Symposium on Computer Architecture (ISCA)* (pp. 213–226). IEEE.

[x19] D. D. Weller, N. Bleier, M. Hefenbrock, J. Aghassi-Hagmann, M. Beigl, R. Kumar, and M. B. Tahoori, “Printed stochastic computing neural networks,” in *Design, Automation Test in Europe Conference Exhibition (DATE)*, 2021, pp. 914–919.

[x20] M. H. Mubarik, D. D. Weller, N. Bleier, M. Tomei, J. Aghassi-Hagmann, M. B. Tahoori, and R. Kumar, “Printed machine learning classifiers,” in *Annu. Int. Symp. Microarchitecture (MICRO)*, 2020, pp. 73–87.

[x21] G. Armeniakos, G. Zervakis, D. Soudris, M. B. Tahoori, and J. Henkel, “Cross-Layer Approximation For Printed Machine Learning Circuits,” in *Design, Automation Test in Europe Conference & Exhibition (DATE)*, 2022, [Online]. Available: <https://arxiv.org/abs/2203.05915>