Tangibles and Computing Education: A View from the History of Computing

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All sorts of objects embody ideas about data and computation through their creation, their application and impact. 'Old' objects also embody histories that are composed of period, location, use, ownership and so on. We explore the nature of historical artefacts and what role they might play in computing education. We argue that encounters with historical artefacts bring students closer to fundamental ideas, themes and issues in both technical and social aspects of computing.

CCS Concepts: • **Social and professional topics** → **Computing education**; **History of computing**;

Additional Key Words and Phrases: historical artefacts, tangibles, embodiment, data and computing before computers, local histories of computing, historical computing collections

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1 Introduction

I will consider computing education and embodiment from the perspective of the history of computing. With 'history of computing', I take a broad interpretation that includes histories of data and computation, their application and impact, and in times before and after electronic computers.[1] I will focus on the use of historic tangibles in contemporary computing education by discussing the nature and value of learning about objects and their historical contexts, and some ways of using them in teaching. I will also discuss creating a historical collection of computing objects for teaching, one that may reflect local interests.

I will argue that historical artefacts can

- enhance student understanding of technical notions
- reveal the context for their emergence, development, application and obsolescence
- pose questions about their influence and value.

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[1] Within this agenda, data communications is included, of course.

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These three effects enable students to engage more deeply with the subjects that the artefacts can illuminate. Further, an historical view can create a panorama in which present and past connect in surprising ways, and that can inform and challenge speculations on the future. Thus, artefacts can

- transform a student's perspectives on computing.

Historical artefacts have the potential to reset a student's personal relationship with study by creating

- new ways of learning and imagining
- experiences that awaken curiosity and emotions
- memories that might be vivid and lasting.

I will also argue that a local historical collection of computing objects, large or small, is an asset in computing education. Students can, of course, be involved in building such a historical collection.

My argument needs to touch upon a number of general topics—rather superficially as none of them are simple—and to discuss particular objects as exemplars. In making the argument, I have chosen to emphasise things that are rather neglected in computing education: I separate data from computation to focus attention on quantification and the use of data; and I favour objects that belong to computing *before* electronic computers, as these focus attention on the nature of historical contexts and their effect on learning. My discussion of objects *after* electronic computers emphasises continuities of data and computation before and after electronic computers.

As to the diverse interpretations of the contested terms 'embodied learning' and 'embodied cognition', I will tread lightly. My concern is with historical objects *per se* and with the kinds of abstractions that they manifest through their form, function and use, and their particular history. I will note but will not pursue the possible effects of objects on students, such as from feelings of surprise, curiosity, excitement, delight, satisfaction, animation, apprehension, anxiety, frustration, discomfort, disapproval and so on. However, I will try to relate historical objects to emerging embodiment taxonomies based on the research literature, e.g., [14, 22, 38]. Historical objects from computing form an interesting special category for new research into embodiment in which emotional aspects of embodied learning and cognition are prominent. More generally, it seems that the relationship between historical objects and embodied learning and cognition needs deeper exploration, especially in science and technology, e.g., [8, 20, 23, 24, 27].

I will suggest some topics or themes in computing that one might wish to introduce or explore with historical artefacts, describing how they can enrich fundamental ideas and principles in computing. This article draws on my own experiences in teaching computing, developing historical awareness, experimenting with pedagogy, witnessing change and building a local collection. This *History of Computing Collection* became one of the cultural collections of my University.[2]

The material elements in this discussion will variously be called *objects*, *artefacts*, *things, stuff* and—perhaps most appropriately given the de-materialised educational context—*tangibles*. Here, the terms will be interchangeable. For brevity, *electronic computer* will be often be shortened to *computer*.

Structure of the Paper. To begin, I will comment on the *de*-materialisation of computing that creates and amplifies *dis*-embodiment. This leads to comments on computing education and curricula in Section 3. Next, in Section 4, I will reflect on the history of computing and on how historical tangibles enhance teaching for which I draw on insights coming from the use of tangibles in teaching general history. In Section 5, I begin to focus on historical tangibles and computing education. Section 6

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[2] Some information about the Collection is here [45, 46] and https://collections.swansea.ac.uk/s/history-of-computing-collection/page/Welcome.

proposes some principles and techniques for mapping a space of pedagogical applications, and forming a historical collection for teaching purposes. The task is to show how to cover computing curricula by designing a classification scheme for collecting relevant objects. In Section 7, I apply the scheme to make a table of 30+ types of object and themes for their use. The next two sections examine some of the objects in the table: objects belonging to the category 'before computers' are discussed in some detail in Section 8; objects belonging to 'after computers' are discussed rather briefly in Section 9. The main arguments completed, in the matter of teaching, in Section 10, I consider how to turn historical artefacts into learning artefacts. In the matter of learning, in Section 11, I briefly address taxonomies of embodiment and the place of histories in an already crowded, complex multidisciplinary space. The two latter topics are ripe for new investigations. The article concludes with some reflections on society and materiality.

2 De-materialising Computing

Computer Science as an academic subject emerged in the 1950s, when computers became commercially available. The take-up was fast as computers fulfilled centuries-old needs in science, engineering, business and administration. Programming became prominent as applications grew in range and ambition. As companies needed staff, training in system analysis and in programming was also met commercially. The universities lost their role in the design and creation of computers, but were able to embrace the brave new world of algorithms, programming and software [30].

As universities developed their own curricula, the physical nature of the computer and its peripherals was obscured by the abstractions of programming, methodologies and tools and their underlying mathematical theories. Historically, de-materialisation is encouraged by: the rise of abstract system theory and its tools for modelling; the demands of reuse and portability of programs; the design of programming languages that are machine independent and universally applicable to problems; the rise of machine independent operating systems and the churn of digital technologies that abstract thinking seeks to ameliorate [30]. More prosaically, until the 1980s, for students of computing to be in the presence of a computer was an event.

This de-materialisation is a primary characteristic of computing curricula, e.g., it separates computer science from electronic engineering. The de-materialisation of computing science continues with rising levels of abstraction in programming, motivated by the needs of understanding; and in automation, motivated by productivity.

Now, to help convey meanings, abstract topics have generic exemplars that relate to the material world, such as terminology, metaphors, 'toy' problems, notional implementations, demonstrations, visualisations, scenarios and so on. The educational notion of *computational thinking* employs a range of computational models to transcend computers and programs [35].

PROPOSITION 1. *There are many pathways from computational abstractions to points in the material world.*

It is through pathways that we can find a vast collection of historical objects, commonplace and rare, with which to make computing education more tangible.

3 Curricula

What counts as essential in computing education? The answer may call for a consensus, but many topics are needed for a comprehensive understanding of computing technology, and there are many computing communities to debate the question. So, in reality, we should not expect to provide a comprehensive education even for the needs of particular communities, let alone a consensus across communities. One topic that, in practice, *seems* to enjoy something of a consensus is history of computing: its position is expressed by its wide-spread absence. Does history of computing belong in computing curricula?

By 'curricula', I have in mind the thousands of curricula that are to be found in institutions and other educational providers. Each design faces timeless questions: What topics to include or exclude from so many specialisms? How deep to pursue them? What level of practical competence and professional awareness should students reach? Answers reflect teachers' perspectives and what they know and, of course, local vested interests; and decisions reflect compromises. Purely managerial considerations also play a part in making priorities: constraints of timetables and facilities, perceptions of the market, the school backgrounds of new students and so on. Such local processes lead to diverse computing curricula, which are beneficial to the discipline, although they can be difficult to compare and accredit. However:

PROPOSITION 2. *Every computing curriculum can accommodate some history relevant to the topics it happens to include.*

So, when it comes to curricula directed at a wide international audience, the extent of technical knowledge is a challenge in both variety and depth. Looking at the ACM's work on computing curricula is one way to appreciate this scale and to track change. These recommendations began in 1965 and were revised in 1968, 1978, 1991, 2001, 2008 and 2013 [15]. In early 2024, the latest report was endorsed by three learned and professional societies, ACM, IEEE and AAAI, and published [1, 37]. This curriculum organises the subject into 17 Knowledge Areas ([1], p. 63), one of which is *Society, Ethics, and the Profession* ([1], p. 269) which has 11 subcategories, one of which is history of computing (pp. 282–283). Creating [1] is a significant undertaking and offers the teacher ideas and inspirations, and a framework for thinking. The portfolio of seven ACM curricula reports offers the scholar an insight into the state of play in computing education over the years.

Computer science sustains a culture that feeds on ideas of change and progress. Its impulse is for the new. It has a self-image that believes computing can make activities better, by being quicker, easier, less laborious, more exact, more accurate, more reliable, cheaper, and more. There are familiar mantras and straplines encouraging people to 'change the world', that predate Apple's innovative 1980s marketing. Indeed, the latest reincarnation of AI has trialled 'disrupt or be disrupted' by the more intoxicated tech evangelists.

Its self-confidence is encouraged by the faith of governments and companies in growth and productivity, and calls for pipelines of skilled computing people to increase them. Since there is no shortage of opportunities for new digital applications, it is easy to cast students as participants in a revolution.

The 'cult of the new' squeezes out topics to keep up with fashionable developments. In some computer science programmes, it is reflected in little attention paid to the physics of chips and displays, logic circuitry, memory components, computer arithmetic(s), computer architectures, firmware and assembler. Knowledge of computer system internals are needed to work with historic devices.[3] Even the rich traditions of programming language design and implementation, and mathematical foundations of computing are squeezed.

However, proposals to involve historical objects in computing education do not depend on debates on curricula. Moving from accommodating history (Proposition 2) to historical objects, we propose:

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[3] Of course, in reality, the physical machine is never far away. In a security course, for instance, there are many reminders of physical characteristics, from data overflows to the electronic echoes of data from a wiped device that specialised firmware can reconstruct.

PROPOSITION 3. *Any computing topic has pathways to historic objects. Conversely, any historic object to do with data and computation can add value to some computing topic.*

4 Using Historical Tangibles

Computing programmes do not seem to value history of computing. Why? Is it *just* the cult of the new?

Universities and schools are places to think about a world outside. In courses that are vocational and professional, students should relate to, and be prepared for, the world they are seeking to enter. Beneficially, history of computing connects topics across the curriculum, strays outside the discipline to other academic subjects[4] and engages directly with the needs and problems of the world through applications. It offers students learning experiences that are well suited to soft skills—dispositions as they are called in ACM Curricula 2023—in a tech-heavy degree programme.

However, a reason that history of computing is neglected is that it seems to demand of teachers and students knowledge that they have not got, nor seems easy to find. So, examining an historical artefact such as a slide rule, or a punched card, offers teachers and students the challenge of making sense of them. It can and should be a *shared* exercise in learning. But what are they learning? In the case of the slide rule or a punched card, the scope is enormous and foundational. Thus,

PROPOSITION 4. *Historic objects are intended to educate the teacher as well as the students.*

The role of objects in education is a fundamental concern of all collections, from great museums and university collections, e.g., the British Museum and Harvard University, to small local heritage museums and galleries. Of particular relevance here is an experiment in history teaching at Harvard in 2011, based solely on artefacts. It was led by Laurel Thatcher Ulrich and reported in *Tangible Things: Making History through Objects* [42]. The experiment was an exploration of history teaching focussed by objects, and by the collection and classification of things. Its concepts and principles did confront established norms of university history teaching. The experiment did not rely on a theoretical framework associated with embodied learning and cognition. It did rely on the treasures of Harvard's collections.

The record of the experiment is rich in examples and observations. Although one cannot do justice to the inspirational examples of *Tangible Things*, from a narrative of reflections on the experiment ([42], pp. 1–20), certain observations stand out as relevant to our purpose; I will extract and gather them together and call them *Ulrich's Observations*:

1. Objects have the capacity for students to take and experience unexpected directions.
2. Questions generated by the object reveal connections between objects, problems, people, places.
3. Objects can change in their use and their meaning.
4. Objects introduce students to new ways of thinking and investigating.
5. Objects create a common space in which teacher and pupil together can ask questions and share discovery.
6. An artefact is intended to be investigated by a method that moves outward in ever widening circles, as its purpose, performance, ownership, use, manufacture and obsolescence are explored.
7. Objects broaden students' knowledge by narrowing its focus.
8. Commonplace objects wherever they may be found are traces of the past.

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[4] Most obviously, the subjects include mathematics, philosophy, physics, sociology, politics and, of course, world, national and local histories.

In the case of Ulrich's eight observations, the historical objects are used to learn history. The distinction between reading historical things rather than reading historical documents is sharp. It is evident in the separation between archaeology and history, and between museums and archives. Theorising historical objects is not new and can play a part in teaching, through philosophical issues of history [20] and science and technology [23].

In our case, the use of a historical object is to learn computing. In computing, there is the same simple distinction, between computers, peripherals and media *contra* books, manuals and magazines. But there are also programs and software that become tangible when brought to life and experienced in execution. Ulrich's observations give expression to some of my own experiences. Some re-appear in this article as propositions.

5 Historical Objects in Computing and Their Meaning(s)

Among the 12 meanings of 'embody' in the current *Oxford English Dictionary* that of giving concrete form to abstract things is best suited to talking about historical objects in computing.[5] Given an object, for concision, we might refer to the abstractions it carries as its 'embodiments'. Conversely, given an abstraction we might refer to an object that manifests it as an 'embodier'.

Applying the terms 'embody' and 'embodied' to artefacts appears to contrast with how it is often used for human cognition and learning, where the embodied elements of an artefact include physical aspects of the learner, with an emphasis on the motor and perceptual systems and how they support learning (cf. Section 11). However, the different uses of the terminology should not prove confusing.

What are 'historical objects'? Historical objects are not simply objects: the adjective 'historical' implies that the object embodies something more. What exactly is that something? It is more than its design, purpose and use relative to a state of the art in some earlier period—its material existence so to say. In general, and especially in the context of education, the historic object points to a history of people and places.

Objects have a *biography*. In engaging with an object there are obvious questions: What is it? What was its purpose? Who used it? But there is also its path in time and space, its period and locations. When and where was it made? Who owned it? How did it survive? What are its meanings and uses now, or may be in the future? Most historic objects lie in a store for most of their 'lives' [7].

The history of an object draws the student away from the technicalities but not necessarily their contemporary relevance. The object's biography secures a past world that is not forgotten. Details prompt questions and reflexive re-engagement with the object and its relationships.

PROPOSITION 5. *The contexts of an historic computing object that are to be found in the biography of the object are a source of embodied learning and cognition. While the computational attributes of the object are expected to be recognisable to students, the contexts may be remote or alien, or close but unrecognised.*

Engaging with material objects of the world commonly stimulates imagination, curiosity, emotions and feelings. The computing topics they embody become more meaningful, understandable and memorable. The topics gain identity and put down deeper roots. Ideally, the combination of technical attributes and historical context of an object should generate surprise.

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[5] A meaning to be found from 1741 is: 'To give a concrete form to (what is abstract or ideal); to express (principles, thoughts, intentions) in an institution, work of art, action, definite form of words, etc.'

6 Creating a Historical Collection

6.1 Cabinets of Computing Curiosities

A collection of objects for educational purposes can have modest ambitions. A simple *cabinet of computing curiosities,* containing material things with commentaries that teachers can draw upon to discuss a topic, can be created quite easily. For example, the transformation of memory size is illustrated by the popular 8-inch, 5¼-inch and 3½-inch floppy disks, with the last as a benchmark: the 3½-inch double density floppy is robust, pocket-size, and typically held 1.44 Mb, which was enough for many purposes at the time. I will return to the floppy later (in Section 10).

An initial plan for a collection, therefore, might reflect some aims of an institution's

(i) computing curricula, and
(ii) research expertise.

Each object will bring with it new connections and perceptions. Thus, soon, if not from the first, the collection plan will welcome and seek out computing artefacts that also reflect local experiences of computing, such as objects that

(iii) reveal computing in the life and work of the local region, and
(iv) are valuable culturally or financially.

For example, for (iii), the computerisation of businesses and administration—payroll, billing, stock, and so on—yield objects belonging to system analysis and early computerisation. These are many and various, such as flowchart stencils, coding forms, rulers for designing machine readable forms for data collection, manuals, specification documents, invoices, brochures, advertisements and local press cuttings. For (iv), the institution's library should retain a collection of older books and journals, photographs and ephemera, that map computing developments over the institution's lifetime.

From modest beginnings, a collection will take shape crystallising around the very act of announcing there *is* a collection in existence. Creating the collection should stimulate some teachers and students to contribute, and to become personally invested in the world of objects and their meanings and connections. A simple collecting plan tied to present needs should soon grow, for the objects will have relevance and appeal wider than computer science programmes, e.g., engineering (simulation), through business (innovation) to media studies (personal and social life) [29].

As any collection takes shape and acquires an identity, the professional world of museums and archives beckon. For our purposes as educators, museum practices and studies are relevant as a source of insight and inspiration. However, their professional standards and accreditation processes need not inhibit the amateur curator. Museums originate in messy personal collections of neglected and undervalued artefacts.

6.2 Collecting Aims, Plans and Outcomes

Computing curricula are largely about data and computation, with some attention paid to their applications and their impact in the world. Thus, we will map the world of objects with these four broad categories: data, computations, applications and impacts.

But, first, there is a fundamental distinction to be made:

computing before electronic computers
computing after electronic computers.

Then, this distinction must be applied to each of the four categories:

data gathering and recording

tools and techniques for computation

applications in sectors

impact on economic, social and personal life.

Thus, we have made eight categories of tangibles for computing education, and for forming a collection. An object can be assigned to more than one category.

Let us consider these choices in general terms before we illustrate them with examples of objects for teaching and collecting.

6.3 Why Data?

Notice that I separate data from computation. Data opens wide a window from which to observe the world and its history: we can see where the need for data arises and we can judge its impact. Thinking independently about data gives us access to concrete applications of note. It also brings to the surface some big themes—of which students are typically oblivious—that lie under the technical topics of curricula, obscured by busy classes, labs and assessments.

Some concrete examples will follow. But first note that data collection and processing have long been common. In industries where the labour force was necessarily large and working conditions arduous and meanly compensated, there was each week the problem of knowing what work a person had performed to the minute in order to prepare their wages to be handed to them in cash at the end of the week worked. Industries with thousands of workers mean data and calculation *at scale*. From the point of view of collecting, potentially, there will tangibles for such large-scale data processing that can be sourced locally.

Proposition 6. *It is the scale of raw data that motivate the development of tools for data collection, validation, recording, processing and evaluation.*

Proposition 7. *It is the growth of new areas requiring or benefitting from measurement and data collection that underpins the development of computation.*

Proposition 8. *The development of computation has fed the appetite to collect data, to use data in discussions and decision making and to decorate rhetoric in daily life.*

This focus on data is relevant to curricula as data science becomes prominent. Students can become familiar with a portfolio of software tools to perform data mining and machine learning but miss the interest and respect that the data itself demand. Data belong to domains outside computing. A path to data is a path into the world. Data for social good and commercial gain go back to 18th Century insurance companies; in our time, it creates global taxi companies with no taxis and accommodation companies with no property.

6.4 Why Computing before Computers?

The distinction between before and after electronic computers is neglected in many curricula—'before' computing is forgotten along with many early, post-1945 developments. However, data and computation before computers are essential parts of the history of contemporary computing and generate many themes that are suited to teaching with objects.

Proposition 9. *Many of the principles, practices and purposes of computation were firmly established before electronic computers. They reveal the raison d'être of computing and of the transformations enabled by electronic computers.*

Astronomy, engineering, warfare, navigation, surveying, logistics, finance and accounting have thousands of years of computation.[6]

The distinction of 'before computers' opens up a world of objects to explore with students. For example, 'before' objects can reveal a society's growing *need* and *appetite* for data and computing technologies; for the student, such 'before' objects can illuminate and map a landscape of the present. Many 'before' objects will be unexpected, bring with them sensations of surprise and fun, and will stir reflection and discussion. Ideally, experiences will motivate, not least a taste for more learning, and change the student's relationship with the subject. Thus, where possible, 'before' objects need to find a place in teaching. Shortly, I will suggest 30+ examples of objects and themes.

Making the distinction raises interesting questions about the historical process of transition from before to after. Technically, what blend of components and functionalities make an electronic computer? One is led to transitions from programs being physical configurations of wires (as in the ENIAC of 1946) to stored programs (as in the Manchester Baby of 1949); and from special purpose devices (such as the COLOSSUS of 1943) to universally programmable machines and languages, meeting Turing's theoretical criteria of universality (of 1936).

The transitions are not only technical, they are what make up narratives of revolutionary change. Throughout the 1950s, transitions of the workplace were everywhere. Very rarely, one can catch sight of them in films, such as *Desk Set* (1957), a romcom with Spencer Tracey and Katherine Hepburn against a background of computerisation. More recently, transitions featured in *Hidden Figures* (2016), about the lives of three human computers working for NASA.

Of course, the distinction before *versus* after manifests in the fundamental and timeless question: What difference did electronic computing make to the world? An examination of the state of play in the 20th Century as science transitions from before to after computers is [3].

6.5 Why Localisation?

To illustrate themes to do with data and computing we expect to be able choose artefacts with connections to many parts of the world and from many historic periods. Ancient civilisations are a source of so many basic ideas. In contrast, the illustration of themes to do with applications and impact can be focussed by regional interests: since computing is everywhere, its tangible effects will not be hard to find 'locally'. For example, for any region—town, county or nation—simple questions that are interesting and yet might be tricky to answer are:

> *When, where and why did computers arrive in the region? What were they?*
> *What were their specifications, e.g., size, speed, memory, power consumption, cost?*

To these the related questions arise

> *Who maintained and used them? Where did they learn their skills? How did computing enter schools and colleges in the region? What social impact did computers have? Were computers and software made in the region?*

And, specifically for the collection (and other local collections):

> *What materials survive that can illustrate these early developments of computing in the region?*

Locally sourced objects carry special vivid and possibly visceral meanings—embodiments for the local population. The potential of local history in life has been memorably described by a young Lewis Mumford (1895–1990), in a talk in 1926 [28]:

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[6] For example, some 4,000 years ago in Mesopotamia, the first empire in recorded history had a complex bureaucracy: recently discovered clay tablets from the Sumerian site of Girsu (= Tello, in Iraq) in the time of the Akkad dynasty (2300–2150 BC), recorded people, materials and expenditures.

> All of us feel, at bottom, with Walt Whitman, that there is no sweeter meat than that which clings to our own bones. It is this conviction that gives value to local history; we feel that our own lives, the lives of our ancestors and neighbors, that events that have taken place in the particular locality where we have settled, are every bit as important as the lives of people who are more remote from us no matter how numerous these others may be; or insignificant we may seem alongside them.

As any collector will confirm: *The provenance of objects matters to people.*

7 Objects and Themes

With our eight categories proposed, the next questions to consider are: What objects and why? Where to source them? What might teachers and students do with them?

7.1 Examples

Here is a selection of examples of types of artefacts belonging to the eight categories, tagged by some ideas and themes that they might embody. The table is intended to create a quick impression of a vast range of objects and general themes they can carry; those marked with * I will discuss in later sections.

Category	**Objects**	**Embodiments and Themes**
Data before computers	Ledgers*	Data collection
	Forms*	Data collection
	Timetables*	Quantifying activities
	Ready reckoners	Popular access to data for calculation in daily life
Data after computers	Punched cards and paper tapes*	Encoding data in physical storage media
	Memories*: drums, disks, cassettes, CDs, sticks	Data storage capacity
	Databases, spreadsheets	Software storage
	Software logs	Automation of data collection
	Web sites and apps	Automation of user-centred data collection
Computing before computers	Early arithmetic books*	Origins of calculating with symbols
	Mathematical tables and slide rules*	Tools for computing by hand
	Mechanical calculators	Mechanical tools for calculation
	Cash registers	Mechanising calculation for security against theft
	Original papers proposing abstract models of human computers*	Logic and origins of AI

Category	**Objects**	**Embodiments and Themes**
Computing after computers	Calculators	Electronic tools for hand calculation
	Personal computers	User experiences and digital domestication
	Programming languages, tools and manuals*	Programming experience
	Games	Graphics
Application in sectors before computers	Gunnery*	Need for data and difficulty of producing it
	Tables for currencies, interest, navigation, tides	Calculations in professional and public tasks
	Clocks and globes*	Time, latitude and longitude
	Time sheets and weekly wages	Data collection and calculation at scale and on time
Application in sectors after computers	Electronic office and enterprise software	Virtual working environments
	Monitoring: recommender systems, and logs	Surveillance
	Mapping the web*	Cyberspace. Electronic commerce and media
	Mapping the earth	Location and mobility
Impact on economic, social and personal life before computers	Census and surveys	Large-scale data collection and its use
	Life insurance scenarios and calculations*	Stable financial insurance and welfare
	Taylorism in manufacturing and office work*	Measuring, modelling and monitoring worker performance
Impact on economic, social and personal life after computers	Blogs and social media	Social studies of the web
	i-phone 1*	Digitisation and convergence of tools
	i-phone 3*	The App Economy
	Digital payments and currencies	Commercialisation
	Blockchains and cryptocurrencies	Identity, contracts, money and crime
	Ephemera: media, ads, flyers, merchandise	Culture. Diversity and equity and exclusion

7.2 Seeking and Selecting Objects

The categories in the table provide a simple format for planning, seeking, selecting and assessing. When objects come to mind, or to hand, one can look for themes they can illuminate. Conversely, identifying themes that shape a course prompt looking for objects.

Let us formulate some guidelines that can be followed in choosing objects and developing a collection:

Proposition 10. *Each object enlarges a student's previous knowledge of the subject and the world to which the object belongs and the subject relates.*

The idea is that artefacts can illustrate topics as they arise in various courses, or become a focus for independent study, or for large scale student investigations through project work.

Proposition 11. *Computing activities, such as programming, system administration and more, cannot be documented easily or adequately described. They are learned through physical engagement and experience.*

This is true of technologies generally, especially those fundamental technologies to do with materials and construction that define ancient civilisations and are found around the world.

Proposition 12. *Computing artefacts whose biographies have significance in general history change perception and engage emotions.*

These propositions point us in a direction where a connection between our artefacts and embodied learning and cognition may be found.

In seeking objects, look in universities and colleges: there are some obvious places such as their libraries, archives and special research collections. In the case of computing, there are also the store cupboards of academic departments and computing services. Department storerooms are the origins of the substantial university museums of scientific history, such as the History of Science Museum in Oxford and the Whipple Museum of the History of Science in Cambridge.

With localisation in mind, access to objects becomes very wide for there are of course the public and private collections in the region which can provide all sorts of connections. There are the second-hand markets that range from international and regional auction houses and web sites, along the lines of eBay, to local shops devoted to raising money for charity, to car boot and yard sales. For computing objects, attics, basements and garages have much to rescue and preserve.

7.3 Interpreting Objects

Objects put particular demands on the teacher. An object requires the teacher to take risks with the unknown when studying its form and function and biography. Objects and the themes they may embody need to be explored.

Does the teacher need to know much about an object? For some objects form and function will need to be understood and demonstrated by use. Consider the standard examples of books of logarithmic and trigonometric tables, and slide rules, or punched cards and paper tapes; all had declined by the 1980s. A teacher will need to learn how these tools were used. Because teachers are unlikely to know a lot about objects, this creates a common space in which teacher and pupil together can find questions, share discoveries and think differently about computing.

Working with objects is suited to investigations by individuals and groups. Rather naturally, teachers can

(i) select historical objects to illustrate technical points
(ii) introduce an historical task in an otherwise full-blooded technical course

(iii) manage practical projects to rescue, assemble or repair objects, including resurrecting software
(iv) supervise scholarly dissertations with a substantial historical purpose.

Thus, student work can be assessed by giving class presentations, writing reports and making videos. I will return to these points later (in Section 10).

8 Commentary on Pre-Computer Examples

We will select a few of the 30+ examples from the Table for a closer look. For a readership familiar with contemporary computing, I will say far more on topics that pre-date computers whose objects and biographies will seem more remote and unconnected. This decision will illustrate Proposition 9 and argue for its importance.

8.1 Data

Contemporary interest in data borders on the obsessional. In computing, data science and its relationship with AI via machine learning is the subject of international political and economic summits. As a commodity, data are controversial as it stimulates surveillance and erodes privacy [47]. However, data are also considered indispensable to argument and decision-making.

In computing we focus on processing data rather than what the data is about. But quantification is fundamental to data and so to computing. It was in the 18th Century that people began to embrace the benefits of quantification in industrial, commercial and social sectors. It begins with a mathematical approach to questions of value, in government finance and in personal needs for sound insurance.

Domestic Records. A ledger is a book in which things are regularly recorded, most commonly these are financial transactions. Ledgers are used for remembering and monitoring via data. There is no shortage of local ledgers to exhibit as artefacts and stimulate discussions—student record books are but one example. The term is central to blockchain technologies for good reason.

In keeping with Proposition 12, one might choose some historically interesting examples. Personal domestic record keeping is a familiar activity and common to many periods and places. One such example is the memorandum books of Thomas Jefferson, who followed Washington and Adams as President of the United States of America. He kept detailed daily records of his receipts and expenditures for some 60 years [6]. Although comprehensive and invaluable for its insights, we also see how such data fall short of representing a life.

Forms. Forms signal a dramatic change in our relation with data. Printed forms are designed for collecting raw data for some well-defined purpose and at scale. There are so many examples to choose from—old and new, significant and trivial. When I lecture on the history of data collection, with Proposition 12 in mind, I show some early examples of the design and use of paper forms. One of the earliest is the form that slave owners needed to complete in 1834 to request their financial compensation when owning people was finally abolished in the British Empire by the Slavery Abolition Act of 1833. The Act provided for a sum of £20 million for compensation. There were some 800,000 slaves in 19 colonies and some 44,000 owners to compensate for their loss [9].

How was it done? Earlier, a matter such as compensation was a matter of personal negotiation. The invitation to the public to fill in a form and send it in was radical at the time. The form codified a systematic process of classifying 18 types of slave; each type was valued at a fixed rate that was appropriate for the economy of each colony. A meticulous analysis of the local market decided on values: for example, in Jamaica an old slave was worth £4 whereas in some other colonies they had no value. The total value of all the slaves in the 19 colonies was found to be some £45 m, whereas the total compensation available was £20 m.

In fact, the compensation operation was a great bureaucratic success: by 1836—2 years! —80% of the money was paid out, and the process could be closed in 1842.

Thus, a form—a single page of text—published in *The London Gazette* on Friday, 18 April 1834, opens up a recognisable world of data collection and processing but in a remote and hard to recognise past situation. It introduces ethical themes of quantification, not least that of the value of human life. We will return to the monetary value of a human life shortly in looking at insurance.

Interestingly, in precisely these years, Charles Babbage's attention was moving away from his Difference Engine to the new conception of his Analytical Engine with its punched cards; and he was introduced to Ada Byron by her mother Isabella, Lady Byron, at one of his famous soirées. Isabella was a social reformer, active in the abolition movement.

Timetables. A source of personal and societal data is time. Consider its collection and recording in timetables. As the railway system grew in Britain, all kinds of complex data gathering and processing innovations appeared. The many private train companies with their own tickets and timetables proved too complex for anything other than radical solutions. For ticketing, a huge bureaucratic operation called the Railway Clearing House began in London in 1842 [2, 4].

For timetables, the problem was deeper than that of ticketing: towns used their own time with clocks set according to their location and the time of year. This variation of time in towns complicated journeys requiring passengers to engage with arithmetical calculations. Timetables gravitated to London time and posters and station clocks began to show local *and* London times. Telegraph infrastructure followed the network of railways and allowed time checks to stations from London by telegraph. This meant that by 1855 the usefulness and accuracy of 'railway time' made it a practical urban standard, and so Britain became a single time zone.[7]

Time has been specified in many ways, often directly based on the sun, daylight and people's physical needs. Examples of objects for its measurement and display can be found in all periods and cultures, and their use involves many forms of data. Geared systems for clockwork lead to historic examples of mechanical automation and data processing in the other categories of computation, application and impact.

Time is fundamental for computers: from the beginning in hardware, with system clocks and synchronization; in programs, with aging data representations such as in Y2K bugs, and Unix's end-of-the-world; and through to the atomic clocks and time signals of GPS and their ubiquitous role in software.

8.2 Computation

Early Arithmetic. Old arithmetic texts and exercise books, especially from elementary schools, record the computational skills desired for pupils and the sort of everyday problems for which they were needed. They have calculations involving weights and measures, units of distance, currencies and interest and dividend payments, that may or may not be obsolete; and they feature cultural scenes from past times. To contemporary computing students, with only pencil and paper, their exercises will seem difficult.

Old arithmetic books demonstrate continuity in the practice of teaching calculation. In Britain, for example, the first major mathematical textbooks in English were written by Robert Recorde (1510?-1558) and were designed to teach advanced ideas to a wide audience. In his arithmetic, called *The Grounde of Artes*, first published in 1543 and in print for 150 years, simple calculations are explained in three ways: using a clever use of fingers, the abacus and the less known Arabic

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[7] Later, the world was divided into 24 separate 1-hour time zones in 1884, at an international conference in Washington, DC. It was based on the Greenwich Meridian, a line through the Royal Observatory at Greenwich.

notation. The form of the narrative is one of a master speaking to a scholar; and the examples and exercises are not unfamiliar. Facsimilies of Recorde's books are available.

Actually, Recorde's four mathematical books form a programme of instruction in mathematics that includes astronomy, commerce, land surveying and navigation; it is precise and quantitative and is based on reasoning that must be open to demonstration and dispute. The history of arithmetic teaching is a rich source of objects and themes.

Mathematical Tools. All numerical calculations are reducible to methods of addition, subtraction, multiplication and division. Calculating with these operations by hand to (say) four decimal places are particularly valuable experiences for students: they are noticeably time-consuming and prone to mistakes. Of course, tools are needed to help calculation.

The computation of additions and subtractions is much easier than those of multiplications and divisions. In the early 17th Century, remarkable new calculating methods were developed by John Napier (1550–1617) and refined by Thomas Briggs (1561–1630) that turned tricky multiplications and divisions into much easier and quicker additions and subtractions, namely *tables of logarithms.* The modern equations have the form:

$$log(x \times y) = log\,(x) + log\,(y)$$
$$log(x \div y) = log\,(x) - log\,(y)\,.$$

The power of logarithms can be experienced by calculating some formulae by hand. A good example is the classical formula for compound interest:

$$A = P \cdot \left(1 + \frac{r}{100}\right)^t$$

Here, A is the amount returned after investing £P at r% for t years. The logarithms work their magic on the exponential t.

Now, addition and subtraction have a physical expression in terms of measurements. When numbers are represented as lengths, addition is combining lengths and subtraction is removing lengths. The creation of ingenious logarithmic scales marked out on linear or circular slide rules can turn multiplication into adding lengths, and division into subtracting lengths. The development of slide rules provides an analogue tool for multiplications and divisions.

Further, there is a long and remarkable development of mechanical calculators. The famed early machines by Blaise Pascal (1623–1662), designed for financial computations, and Gottfried Wilhelm Leibnitz (1646–1716), for arithmetic calculations using binary, loom large. Among major landmarks in their progress, there is the large-scale Difference Engine of Charles Babbage, and the popular portable mechanical calculators of the Odhner and Brunsviga companies, which can be obtained for students to experience.

Abstract Models. Abstract notions of computation that are central in contemporary computing actually predate computers. They can be talked about as notional machines and they can be made tangible by objects. Two examples are the

- *Turing machine* of 1936
- *neural net* of 1943.

The concepts are alive and well in our curricula.

For this theme, rather than discussing physical realisations—such constructions in wood, metal or Lego bricks—the objects to select are the original academic journals in which the ideas appeared. These objects connect the student's modern curricula with both the imaginative, curiosity-driven thinking of gifted mathematicians and scientists, and to the long-established philosophical traditions and scientific discoveries that lie behind them. They also offer the student new experiences of methodologies and epistemics of computing.

The biographies of these objects are rich. To understand Turing's logic is to engage with philosophical questions that had been made precise using the then newly developed ideas of formal logic in mathematics. More practically, Turing's notion of a universal machine is the source of a precise definition of general-purpose computer: the Church-Turing Thesis of 1936, on the scope and limits of algorithmic computation,[8] is used to characterise a general-purpose computer and its general-purpose programming languages. Here, a discussion of the ideas of computer *versus* calculator arises naturally, both historically and technically.

To see McCulloch and Pitts is to engage with the mathematical possibilities of modelling the behaviour of neuronal structures as spatially extended computers with parallel components. From 1947, Turing machines and neural nets were influential in John von Neumann's abstract thinking about the design and programming of stored-program computers *before* they existed. With these artefacts a discussion of the metaphor of a 'brain as a computer' arises naturally.

To these can be added their post-computer legacies such as *finite state automata* whose theory begins in earnest in 1955. Ideas of finite state machines arise in several heads sometimes inspired by control mechanisms that were ubiquitous in the War. Their modern mathematical form was settling down in 1956 when Stephen Kleene showed that as models of computation, neural nets, finite state machines and regular expressions were equivalent in computational power [36].

There are other examples of 1930s legacies: Alonzo Church's invention of *lambda calculus* of 1934, which inspires LISP and advances significantly the agenda of AI, and also defines the functional programming paradigm; Emil Post's *symbolic systems* find their way into Noam Chomsky's grammars. Garrett Birkhoff's work on general or *universal algebra* of 1935 was to become the heart of the theory of abstract data types and their specification; and his *lattice theory* in 1940 has found applications wherever orderings and hierarchies can be found, e.g., in programming semantics and security.

This parade of stunning exhibits from logic underlines the importance of mathematical theories, and speculative thinking.

8.3 Application

Advanced applications of computations abound in astronomy, navigation, and ballistics. Each of these three fields of applications possess striking examples of computational methods and achievements, starting with the writings of ancient Greeks and Romans. For example, Greek astronomy has profound examples in the Antikythera mechanism, the calculations of Aristarchus and Eratosthenes, and Ptolemy's star catalogue and trigonometry [32]. Calculations in these areas come to fruition in the 17th and 18th Centuries following developments associated with Galileo and Newton.

Ballistics. The Greeks and Romans had formulas for catapults that were based on weight of shot [33]. As the power of projectile weapons is transformed, the process of measurement, modelling and computation develops. Indeed, the technology of cannons develop to a level where the fruits of the theory of projectiles must pass from scientific texts into necessary data manuals for gunners and their guns in the field. Examples of gunnery tables are not hard to obtain.

A *gunnery table* is a manual containing tables of data to allow gunners to take measurements and make estimates (of calibre of shell, distance to target, wind speed, humidity and range to name a few) and then look up in the tables the values that are the parameters for aiming their weapons.

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[8] The thesis is commonly formulated as: a function is computable by an algorithm if, and only if, it can be computed by a Turing machine.

These tables are the product of huge numbers of complicated calculations. Many scientific people found their themselves working on ballistics in World War II.

The early and most famous American electronic computer was the ENIAC, built at the University of Pennsylvania, and designed for computing gunnery tables. ENIAC means *Electronic Numerical Integrator and Computer,* which reflects the mathematics it needed for the tables. Its cost to the US Army at $487,000 in the money of the day distinguishes the problem it was intended to solve [13]. Note that the Harvard Mark II was an electro–mechanical machine for ballistics commissioned by the US Navy at roughly the same time, and built between 1945 and 1947. Today, ballistic computations beyond those of the ENIAC are available for hunters in inexpensive apps for smart phones.

Ballistics has thrived as cannon are joined by rockets and missiles. The precision weapons and counter-measures we have become used to seeing deployed on news feeds involve the satellites of the US Airforce GPS, which became fully operational in 1995 and released for civilian use in 2000 by President Clinton [43]. GPS brings us to longitude and the measurement of time.

Longitude. Calendars and clocks are objects that embody the complex physical origins and nature of time, measured by years, months, days, hours, minutes and seconds. Globes and maps model and formalise the equally complex physical origins and nature of location and position. There is an extraordinary wealth of examples of clocks and globes from which pathways quickly lead to the collection of astronomical data and the mechanisation and automation of computations. The invention and measurement of the fundamental data of time and location offers thousands of years of tangibles, from the Antikythera mechanism (time) and Ptolemy's Globe (location) to satellite navigation (time and location). From such examples, consider clocks and globes and the problem of longitude.

Latitude is defined in terms of a fixed locus, the equator, that bisects the world and appears the same in all places and at all times. The calculation of latitude needs relatively straight-forward techniques to do with the position of the sun and was known in essence from ancient times. Because the earth rotates, the calculation of longitude is more difficult to measure against a fixed line. Calculating longitude was recognised a major problem for the expanding navies and merchant shipping of world powers. For example, in passing The Longitude Act of 1714, the British Government challenged the scientific community of the early 18th Century, offering a prize of £20,000 to *anyone* with a *practical* solution to the problem of finding longitude at sea, to an accuracy of half a degree.

The division of the spherical earth into longitude lines correspond with time: a day is a rotation of the earth and is divided into 24 hours; we measure angles by 0–360 degrees. Thus, the creation of longitude lines $360/24 = 15$ degrees apart corresponds with the passing of an hour. So, if you know the time where you are and compare it to the time at home you can work out the longitude. At sea the navigator would use instruments to estimate the time but needed a clock to record the time at port in order to complete the calculation of longitude. The clocks of the period failed to keep time accurately enough at sea and were subject to physical distress. Many solutions to the longitude problem accumulated, but they did not prove practical. John Harrison (1693–1776) ultimately solved the problem with a series of clocks known as H1–H4, whose novel mechanisms could keep Greenwich time at sea and so enable sufficiently accurate computations of longitude. The story behind this is long and full of surprises and has been the subject of a popular book and film [39].

8.4 Impact

Insurance. Data science is a newish collective name for ideas and methods for the gathering, analysis and application of data, notably in data mining and machine learning that has breathed new life into AI. Relevant to all four categories is the task to map the rise of data in the world. For an example of impact, I have chosen the emergence of life insurance in the 18th Century and one book that is its embodiment: Richard Price's *Observations on Reversionary Payments,* first published in 1771.

Richard Price (1723–1791) was a dissenting minister, philosopher and a political radical. He was a close friend of Benjamin Franklin and heavily involved in supporting what became the American Revolution. He was also an able mathematician. There is a wealth of material available about Price [10, 44, 40].

Price enters the commercial world of pensions and insurance by being asked for advice about a scheme by lawyers to create a fund for widows of their profession; Price found the scheme unsound and it was abandoned. Later, in 1768, Price was asked about a problem faced by the newly formed Society for Equitable Assurances on Lives and Survivorships; they consulted and acted on his recommendations for the next 15 years. The Equitable prospered and became a role model for a new data-intensive industry.

To Price, financial projects to create pensions and insurance were designed to bring security to the lives of people (especially women and children), and they were self-evidently moral acts that met obvious needs to improve the welfare of society. But, in the 18th Century, they were commercially novel and vulnerable; indeed, they were likely to fail, meaning penury or destitution for beneficiaries. The problem was: what might be a business model that could be practically realised and sustained? At the heart of insurance is the risk involved in providing funds decades hence: what can be known about a set of lives in the future?

A theory of insurance had been started by an investigation by the astronomer Edmond Halley (1656–1742). He had acquired some statistics of births and deaths over a 5-year period from Breslau (now Wrocław in Poland) and explored what use such data might have, including its relevance for estimating probabilities of life and insurance. These observations were taken up by the mathematician Abraham de Moivre who was pioneering the theory of probabilities and postulated simple formulate that *might* generate approximations to such data and enable calculations on a larger scale in the absence of better data in a life or mortality table.

A life table can have several forms. A row in the table might look like

Age	Living	Deceased
n	a_n	d_n

The life table offers a way of calculating the probabilities $p(n,m)$ that someone lives from age n to age m where $n < m$. One looks up the number a_n of people alive at age n and the number a_m of people alive at age m and works out the fraction

$$p\,(n, m) = a_m/a_n.$$

But what is known of these numbers a_m and a_n and how representative might they be for general use?

Price recognised that what was needed was a probability theory firmly based on reliable data on lives of the past. He recognised that any data needed careful curation before its integration into this application. The provenance, evaluation, aggregation, etc. of data need to be considered in order to judge the relevance of the data to a particular problem and to the interpretation(s) of the solution(s) in which the data are used. By rigorously isolating and examining concepts and assumptions, and especially comparing different mortality data sets, Price's work was devoted to curation as well as calculation. It also made the case for the need for census data [11].

The *Observations* is his mature collection and analysis of data and the use of mathematical methods for designing life insurances. It covers:

- Collecting and reflecting on raw data on populations

- Designing and creating tables of data that can be applied practically and so need to be sound and comprehensive
- Reflecting on data and calculation methods
- Calculating basic probabilities of events
- Methods for the calculation of complex insurance scenarios
- Tables of extensive financial calculations for insurance scenarios.

Price's *Observations* ran to seven editions. The first three editions came out in 1771, 1772 and 1773, respectively. Each had changes and more tables. A decade later Price published his fourth edition in 1783. This was a major revision, 4 years in preparation. It now formed two volumes, half of which was new material. Among many life tables he analysed, in the fourth edition, Price advocated a table of data from Northampton, based on the Bills of All Saints Church for 46 years (1735–1780). The Northampton table was used by the Equitable and became famous as a standard tool in the first century of insurance. This fourth edition is available in facsimile, as are earlier and later editions.

There are more reasons for computing education to engage with Richard Price and his world. Probabilistic and Bayesian methods are likely to be in the curriculum as they are applied everywhere [25]. Their origin is the Bayes-Price Theorem on inverse probability of 1763. Before his work on insurance, Richard Price prepared for publication some theorems about probability theory he found among Thomas Bayes's papers. Editing, refining and supplementing the work, he created papers that expanded the mathematics, pointed out its originality and technical importance and recognised its significance for science [5]. Price made the very first application of the theorem in a philosophical argument with the philosopher David Hume over the nature of oral evidence for miracles. The quantifying and calculating spirit are embodied in Price, including in his religious, ethical and political writings.

Scientific Management. Automatic collection and communication technologies based on digital data have been changing industrial control systems and manufacturing since the 1950s. The scientific approach to manufacturing begins to take hold in the late 18th Century. Manufacturing was well advanced in matters of materials and physical processes, when a scientific approach was advocated toward the labour of making things, promoted in Adam Smith's *An Inquiry into the Nature and Causes of the Wealth of Nations* of 1776. Smith's ideas took root. In the early 20th Century, the new manufacturing paradigms of assembly lines, time and motion studies, monitoring, and formal planning and organisation, can be traced back to Frederick Winslow Taylor (1856–1915): his studies started in the steel industry, notably in the Bethlehem Steel plant, and was published in *The Principles of Scientific Management* in 1911.

His approach was based on observation, measurement, planning and monitoring worker performance; it was new, revealing and generally applicable. It is still referred to as 'Taylorism'. The growth of scientific management as a movement introduces students to people such as Henry Gantt (1861–1919), likely known for his chart for project planning and performance analysis, and Carl Barth (1860–1939) who designed application-specific calculating tools when working with Taylor at Bethlehem. But, for our purposes, of more direct interest is the transition of scientific management from the factory to the office. William Henry Leffingwell (1876–1934) seems to be far less well known, but his texts such as *Making the Office Pay* (1918) and his founding of the National Office Management Association left a mark on offices and on labour in general. For example, his *The Automatic Letterwriter and Dictation System* (1918) with its trees and flowcharts, devoted to uniform and efficient correspondence by letter, suggests architectures that shaped system and workflow analysis and modern enterprise software systems. See his textbook [19].

Thus, these texts and their associated objects—slide rules, calculators, tables, charts, templates, advertisements, floor plans and so on—point to computing practices that can be found in modern day-to-day software tools. They also relate directly to social issues such as the standardisation and regimentation of labour via rules, micro-management of people via monitoring, and its automation by software, which has been in progress for some decades.

9 Commentary on Post-Computer Examples

In entering the era of electronic computers, there is an expectation that the selection, collection and interpretation of objects and themes become much simpler. Objects are likely to be easier for teachers and students to recognise and use, and to discover their biographies; they will also be easier to obtain. Teachers and students are on home ground.

For the era of computers, there is significant help in the form of Kim Tacy's textbook [41]. There, the modern curricula around software are explored historically with pertinent examples and commentary, exemplifying admirable concision and taste. Indeed, the availability of [41] is another reason I need say less here.

With these expectations, I will select just five post-computer examples from the Table for comment. Some are intended to connect with the pre-computer examples, and so support Proposition 9 about continuity.

9.1 Data

Punched Cards and Paper Tapes. A punched card physically embodies the concept of an instruction and of a datum. Punched cards encode using the binary distinction of hole or no hole. The patterns of holes on the card are codes that represent instructions and data. Paper tapes are similar in nature in this respect. Both cards and paper tapes were fundamental to programming early computers and were still common in the 1980s. Cards differed in size, number of columns and rows, the shapes and sizes of holes, and what the pattern of holes in a column meant. The common format of 80 columns, 12 rows and rectangular holes was introduced by IBM (for their electro-mechanical equipment in 1928).

With cards, writing programs is physical and needs a range of machines. Preparing a card involves punching, verifying that the information on the card has been correctly punched, sorting large numbers of cards into ordered sequences and groups and tabulating. Decks could contain thousands of cards. Computer companies needed to provide ingenious machines to cope. Comparing cards and tapes is a way of grasping the attributes of scale and speed of data handling, e.g., through estimating how much bits of data can be processed per second by these and later media.

Selecting punched cards as a post-computer object focusses on continuities in the transition from electro-mechanical data processing to data processing by electronic computers of the 1950s, 1960s and 1970s. The pre-computer data processing capabilities of IBM, Powers-Samos and other companies were advanced and widely spread around the world. Millions of punched cards were consumed by government departments and companies: two significant historic episodes are identifying Jewish people in Germany in the 1930s, and in the cryptographic operations of Bletchley Park in the 1940s.

Punched cards are an invention of the early 18th Century. They were created to program looms to weave different fabric patterns and perfected by Joseph Marie Charles Jacquard (1752–1834) in the early 19th Century. Programming with punched cards entered computing when Charles Babbage adopted cards for his Analytical Engine, and Ada Lovelace pointed out their profound flexibility in forming sets of instructions. The idea of programming with punched cards spread to automate machine tools and musical instruments.

Tapes have a closely related history. Jacquard's improvements included chaining cards to make tape-like objects. The early telegraph used tapes extensively for alphabetic encodings not unlike the ASCII codes standardisation of the 1960s.

9.2 Computation

Programming Languages. Programming languages are at the heart of computing education and are a rich source of objects and themes. Languages express algorithmic ideas and are well supported by tangibles: program print-outs and executions, coding sheets, manuals, crib sheets, specification and standards documents, textbooks, interviews with designers and programmers, and controversies. Since programming languages are used everywhere in computing, there is a wide choice of themes for which pathways associated with programming artefacts can be found. In selecting themes, one can work chronologically forward from the early languages of Fortran, COBOL, Algol, PL/1 or Pascal, or backward from common languages Java or Python.

There are thousands of programming languages. Languages invite comparisons. Some semblance of order is established by classifying languages as imperative or declarative, compiled or interpreted; or as object-oriented, functional or logic; or as real-time, scripting, safety critical or memory-safe; or as concurrent, non-deterministic and more. The distinction between general-purpose programming or programming for specialised tasks and niche areas leads back to the Church-Turing Thesis and the limitations of weaker computational models, such as finite state automata.

The growth of programming languages and methodologies provides a wealth of material for a history of computing abstractions, e.g., through the interplay of data structures and algorithms in their design. In studying the development of languages, we engage in a process of deconstruction and reconstruction of these abstractions.

9.3 Application

Mapping the Web. The personal computers that became available in 1977 created a large market. Users at home were serviced by magazines devoted to particular brands to provide news and, especially, new programs for readers to type in and run. These magazines record personal computing in considerable detail, with articles on devices, their specifications, reviews of performance, interviews with personalities, lists of prices and retailers.

The 1980s abound with new developments in personal computing, not least the Macintosh, the rise of gaming and connections to the Internet and transferring files. When the World Wide Web became publicly available in 1993, some computer magazines gave free, large-scale paper maps of Internet web sites as pull-outs. These paper maps are fascinating objects to study as they combine sites of all sorts of organisations and individuals at all sorts of places.

9.4 Impact

Smart Phones. Like the personal computer, the so-called smart phone is destined to be era-defining in digital technology. Its significance is more than its physical attributes of compactness, mobility, connectivity and user experience; and is more than the hundreds of inventions that needed to converge to create it. In addition to its attributes and innovations, the smart phone embodies the grand theme of digitising the world.

What we now recognise as a smart phone begins with the Apple iPhone, which was styled at its launch in 2007 as a music player, phone and Internet communicator. It had 16 apps all made by, or in collaboration with, Apple. They formed a 4 × 4 matrix: SMS, Calendar, Photos, Camera, YouTube, Stock, Google Maps, Weather, Clock, Calculator, Notes and Settings; and below the matrix was Phone, Mail, Safari and iPod.

Tracking the addition of features to the iPhone, and the rise of the App Economy, are two exercises that require the student to engage deeply with many important computing technologies and with the intriguing process of innovation and commercialisation. For example, in 2008, came the iPhone 3G, which had GPS and so added directions to maps; more significant was that the 3G allowed third-party apps via the new App Store and an App Economy was born. Siri came with the iPhone 4.

The early history of the iPhone and of the technologies that it brought together from around the globe is quite fascinating and told with compelling thoroughness in [26].

10 Teaching and Learning Using Historic Tangibles

An historic artefact prompts investigation of its form and function, its intended purpose and actual use, its period and place and its individual history. I have argued that an historical artefact can enhance teaching and learning by revealing these aspects and addressing its development and context. Separating data and computation, and before and after electronic computers, expands the choice of artefacts and introduces new ways to envision computing.

In this section, I pose and comment on the question:

> *In what ways might a teacher turn a historical artefact into a learning artefact?*

which deserves new educational research and fieldwork.

10.1 Teaching with Historical Objects

What does good teaching with historical objects look like? I will offer three simple scenarios involving university students. The examples illustrate

(i) Classes: using an object as a prop in a lecture or tutorial;
(ii) Teams: investigating and reporting on objects in small groups in a class or lab;
(iii) Individual: project work.

First, it is necessary to bear in mind the age and personal experience of students. In 2025, the year of this article, a computing student aged 18 is as old as the iPhone—personal digital services such as Twitter/X is 19 years, Facebook is 21 years, and Amazon is 31 years. For some of these students, a textbook is becoming an historical object. So, what makes an object historical is a point worthy of discussion.

Second, the historical context of an object may need an explanation that is simplified and elementary. Students' knowledge of 'recent' historical events, such as of the 20th Century, will doubtless need priming.

10.1.1 Historical Props and Demos in Class. Consider introducing an object into a conventional lesson for students to handle and inspect. The object interrupts the familiar flow of information from the teacher. Students are prompted to expect to have to do something and field questions. The suspension of the lesson's normal pattern may help students who are struggling, falling behind, or not interested for whatever reason, to re-engage. Students cannot predict what's next and have to pay close attention. Of course, what does happen next is open.

For example, consider the 3.5-inch floppy disk, which is available in bulk. Suppose a lesson starts with asking about the commonly occurring icon for saving a file and then handing out floppy disks to be examined by a class. I will consider two technological directions for the lesson to take, both of which have considerable technical and social impacts:

(i) data storage and transportation, or
(ii) interactive displays and user experience.

How much data does someone need? As a landmark in data storage the 3.5-inch floppy is compact, robust and portable. Its common capacity of 1.44 Mb can calibrate data possession in the first decades of personal computing. A floppy was practical, perhaps containing hundreds of pages of text 'in your pocket'. In 1980s personal computing, accessories like leather wallets designed to carry four floppies on the move, and hard plastic caddies designed to store 100 floppies at home, became commonplace. Several paths open up to do with the technical development of memories and their impact. As digital images, sounds and videos become common, personal digital archives become enormous: the floppy cannot accommodate one image taken with a smart phone, but people's smart phones quickly accumulate thousands of images with little effort.

System and application software was delivered on floppies: a demonstration of installing, say, a word processor on a personal computer of the early 1990s would provide some entertaining and memorable choreography as many disks are inserted and re-inserted into drives.

The distribution of data is a perennial problem for large amounts of data, so the emergence of file transfer protocols for the Internet arises naturally. At CERN, a central task was to distribute *vast* quantities of data to physicists around the world to use in their research. This was done by posting cassettes. The World Wide Web was developed at CERN to help solve this problem of sharing information. In many universities, including my own, the web first arrived in physics departments with particle physics researchers.

Alternately, the path to user experience is well trodden. In the first edition of 1988 of Don Normann's celebrated *The Design of Everyday Things* ([31], p. 28), he describes concisely why the 3.5-inch floppy is an example of good design.[9]

Returning to the floppy icon for save, explicit comparisons between what might be seen on the Apple MacIntosh and other personal computers running Microsoft DOS in 1984 are profound: side-by-side comparisons of screens featured in magazine advertisements. The floppy and all the other icons for the Mac were designed by Susan Kare. Icons revealed the power of visual cues that are physically situated in the screen and accessed via the physical movement of the mouse. The popular use of bitmapped displays in user-focussed industrial design essentially takes off here.

The physical structure of floppies and disk drives are complicated, with their sectors and tracks, disk formats, and actual capacities. Obviously, they can be used to initiate students into taking interest in memories. But the floppies also offer teachers a *pons asinorum* for computing: advanced numeracy. Memory size, processor speed, transmission speed, screen refresh, transistor integration and even market capitalisations of companies are all prompts for training in physical units and large numbers that are of interest in computing. For quantification and scale, memory seems easiest to contemplate and build intuitions.

Perhaps the de-materialisation is illustrated by the unfamiliarity of many computing students with the physical units and quantities that shape computing practice despite them being everywhere (e.g., even standard terms like hertz, terra, giga and nano are poorly grasped). Any discussion of memory is also a discussion of big numbers that are cognitively troublesome.

For disks, first, there is the confusion between units: binary with 1K = 1,024 and 1M = 1,048,576 *versus* standard decimal with 1K = 1,000, and 1M = 1,000,000. Second, there is what do these memories mean in terms of encoding. The opportunities for quantitative exercises comparing capacities are many: e.g., how many floppies equate to a 16-gig stick or a terabyte disk?

Third, there is the exponential scaling up to explore giga, terra, peta, and so on. To appreciate large numbers, one can apply the number to counting time or money. For example, if

$$1 \text{ gig} = 10^9 = 1{,}000{,}000{,}000$$

then 1 gig's worth of seconds translates into near 32 years. To continue the exercise with

$$1 \text{ terra} = 10^{12} = 1{,}000{,}000{,}000{,}000$$

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[9] Originally called *The Psychology of Everyday Things*.

then 1 terra's worth of seconds translates into near 32,000 years. To illustrate, in August 2020, Apple became the first company to have a capitalisation of $2b, just 2 years after it had achieved $1b. So, if a student handed out a $1 bill every second, then it would take near 64,000 years to complete the pay-out $2b.[10]

Billions and trillions are common in the financial world, but they do not make sense in the everyday physical world of bills and coins. One might propose a discussion on: *Money is an abstract data type that is embodied by cash but not implemented by cash.*

10.1.2 Team Exploration and Interpretation. Consider a setting where a class is divided into teams or groups and presented with objects to investigate. The set of objects may have a common educational purpose, representing a technical topic or general theme. The groups could report orally, write an informative label that would accompany the object if on display, or a longer note on it suitable for a visitor's guide to an exhibition.

Interrogating an object means formulating questions such as those in Section 5 that motivated the idea of the biography of the object. One can shape the task by creating a template: a simple one would be

Object.	A description to identify the object.
Period and purpose.	A description of when and why it was created.
Biography.	An account what is known about the object.
Pathways.	Connections with contemporary computing.

These four characteristics seem sufficient to guide an exploration of an object by students. In fact, they can also serve as an easy-to-read register for objects in a cabinet of curiosities.[11] How these characteristics are developed will depend on the objects; it is expected that the Pathways heading is particularly important as it invites reflection on continuities and discontinuities and fixes the place of the topic in computing. Although objects in Sections 7, 8 and 9 are very different, they are possible candidates for such an exercise.

Development typically involves precursors. For example, if the groups were given a range of 8-inch, 5.25-inch and 3.5-inch floppy disks in addition to the directions suggested in Section 10.1.1, the pathways could move on through zip disks to the memories using USB technologies. Memory development deserves a far wider and longer-term view in collecting and interpreting objects.

Ideally, objects would include working devices, systems and software, which are best suited to a lab setting. This form of group classwork should not be confined to technical topics. Social, economic and political topics are also possible with objects such as newspaper articles, government reports, advertisements, images, video and merchandise.

10.1.3 Individual Projects.

Proposition 13. *An aim of university education is to give students the ability to learn complex new subjects unaided.*

In computer science education, this aim is commonly supported by supervised project work over the course of an academic year.[12] For some curricula, the choice of projects is wide, encouraging supervisors to propose all sorts of questions and tasks that interest them, or allowing students to propose their own. For other curricula, there are constraints on the kind of project, requiring

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[10] A classroom demonstration will confirm it is not easy to keep up a rate of handing out $1/second.

[11] It falls short of what is needed for cataloguing the object in a collection.

[12] Another way of supporting the aim of giving students the ability to learn complex new subjects by themselves is to have courses with individually chosen historical assessments [45].

substantial practical work, notably programming and/or applications development (e.g., to meet professional accreditation bodies).

In any case, the student should admire the aims of their project, be keen to invest in the prerequisite learning and investigation and own the results. The suggestion is to make historical perspectives an important part of the project. Ideally, the project should engage some passion. A student's formative interests in computing is a place to look for topics.

Historical projects involving artefacts easily can combine scholarly investigation, technical development and field work in varying degrees. Such project work can pick up topics that have become shallow or been squeezed out of the curriculum. It can also serve the ambitions and needs of a local collection.

Technically, there are projects galore in resurrecting old machines, systems and software. With old systems, students may enter the world of emulations which has excellent educational credentials. Students can learn about the details of architectures; the effects of varying word sizes on portability; the evolution of system software as operating systems change and explain and tackle difficulties in rescuing applications, such as recreating old games on new machines. They also learn first-hand of the problems of digital preservation.

For programming, there are methodologies and tools for system analysis and program specification and design. There are old programming languages to learn from old textbooks, old physical and software tools to employ, and the task of understanding their origins, growth, impact and decline. Systems analysis, form design for data collection, and COBOL certainly make a worthy student project.

Present-day social, economic and political topics depend on their past and tempt speculation on their futures. For example, the topics of monitoring and surveillance, data privacy and digital identity, or the rise of big data, machine learning and generative AI, have significant historical, technical, ethical and cultural themes that need to be integrated. Such projects can be called technically informed 'histories of now'.

11 Perspectives on Embodiment

Embodiment as a theme in education owes much to embodiment as it arises in subjects such as anthropology and psychology. Educationalists have attempted to characterise and classify embodied learning and cognition based on a truly multidisciplinary research literature. For example, the survey and scheme in [38] offers a 2D framework to classify embodiment. Its classic x, y axes are based on task integration (marked incidental and integrated) *versus* bodily engagement (marked low and high); thus, it is represented as a square with four quarters.

Experiences with historical objects in computing invites empirical and theoretical research in order to benefit teaching. Here, as foundations, I have relied upon circumstantial evidence based on the field work that underpins Ulrich's Observations (in Section 4), and my own experiences as a practitioner. A theoretical question that deserves investigation is:

> *What might encounters with historic artefacts mean for theorising embodied learning specifically in computing?*

Now, educational research theorising embodiment goes far beyond the classroom, as it is feature of a *materiality turn* in humanities and social studies.[13]

The breadth of thought that underlies, inspires or informs the material turn is vast and controversial. Research and scholarship in psychology, anthropology, social studies of science and technology,

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[13] A *turn* in scholarly studies is a new, separate direction of research with a coherent set of concepts, theories, problems and more. The material turn is a movement emphasising objects and their ontology.

archaeology, and historiography provide ideas, critiques and evidence for characterisations and classifications of embodiment in education; this is seen in literature surveys. For example, there is a traditional focus on artefacts in archaeology and anthropology and, as a search for their meanings broadened, deeper theoretical questions about materiality in society and culture have emerged and been pursued. Goods help constitute personal and social worlds. Among many works, the mature reflections of Tim Ingold in [16] on his discipline of anthropology are engaging. Some abstract theories have emerged that have found wide application, such as actor-networks of Latour and his colleagues in social studies of science and technology [17, 18]. Here, the concepts of assemblages of actants are used to re-construct knowledge, wherein actants can be human or non-human, and all have agency. Actants include artefacts.

The materiality turn, and studies of embodiment generally, find roots in philosophy. The philosophical influences/credentials of this multidisciplinary literature largely appear in French post-war philosophical discussion of the places of body and mind in 'being' (e.g., Merleau-Ponty, Sartre, Foucault and Bourdieu). However, one of the papers that presents a general classification of embodiment in education allows me to highlight a philosophical analysis of embodiment that belongs to the era before computers [14].

Where the influence of Merleau-Ponty and Heidegger is significant, then it is appropriate to draw attention to their common philosophical mentor. They were both pupils of the mathematician and philosopher Edmund Husserl (1859–1938) who engaged in a phenomenological pursuit of the foundations of mathematics and science. Over a lifetime, Husserl's epistemology evolved a philosophical 'theory of the body' as he sought new foundations for what we know and how we might know it. This theory has been recovered and explicated by Lanei M. Rodemeyer and, furthermore, applied to contemporary topics like gender [34]. As the starting point for a general survey of embodiment in higher education [14], Husserl's theory of the body, as identified and framed by Rodemeyer, is adopted; Hegna and Ørbæk re-name its five components with simpler terminology for the purpose. This makes a welcome direct connection between epistemology and embodiment in education.

12 Concluding Remarks

Historical objects can make tangible topics in computing that are abstract and are displaced or isolated from their origins and uses. Through objects and pathways our sense of computing as an academic discipline and profession grows because its abstractions and technicalities can be situated in and connected to the world at large, past and present, in narratives of technical and historical significance.

Proposition 14. *The disembodied natures of data and computing are intrinsic. As the technical depth, reach and significance of digital technologies have expanded since the 1940s they have encouraged and created disembodied ways of living and working and of viewing the world.*

This evolution is worth examining in computing education. Digital abstractions and their propensity to create automations that remove people from actions and decisions have often been inflicted with little attention to their long-term consequences. But note that some trends long predate the computer age—recall the example of scientific management in Section 8.4.

We have examined the nature and use of 'historical objects' in computing education. The diversity of objects and the extent of their embodiments are quite vast. We have reported on a framework to develop and manage a collection of objects for education. The student work we have mentioned can certainly reinforce the teaching of individual knowledge areas, and generic educational aims, especially independent learning and what is referred to as soft skills or 'dispositions' ([1], p. 56).

As objects are sought for certain topics, the framework's eight categories of object may need refinement, e.g., to better suit themes like remoteness, with examples to do with data centres, networks and cloud infrastructures; and globalisation, with examples focussed by national jurisdictions and labour markets.

Characteristics of embodied learning, such as perception, action and emotion in various combination, are to be found in students engaging with historic computing objects. Objects are to be handled, manipulated and puzzled over. Objects can open up wide perspectives on data and computing, especially on its fundamental concepts, methods and applications, many of which are of the past. In action, there are the physical experiences with hardware, software, locations and people. In emotion, there is surprise and the exercise of imagination in being confronted by the past.

The power of objects is well known through museums and auction houses. In 2010, listeners to BBC Radio 4 for 20 weeks or so were regaled with *A History of the World in 100 Objects* by Neil MacGregor, then Director of the British Museum. The objects were from his museum and each was the subject of a 15-minute talk.[14] This massive and difficult project was far more than a *succès d'estime*. Certainly, it celebrated objects and their embodiment of the past and inspired diverse projects with an intention to remind us of the power of material objects to intrigue, investigate, inform and remember [21]. Some objects he chose to write about belong in our collection.[15]

The format is flexible and easily adapted to a region: for example, for my own country, Andrew Green, the former Librarian of the National Library of Wales, produced his *Wales in 100 Objects* [12]. A teacher might like to think about *A History of Computing in 100 Objects,* albeit tailored to computer education; and invite help from students to do so.

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