ABSTRACT

In Fall 2020, Harvard University transitioned entirely from on-campus instruction to Zoom online. But a silver lining of that time was unprecedented availability of space on campus, including the university’s own repertory theater. In healthier times, that theater would be brimming with talented artisans and weekly performances, without any computer science in sight. But with that theater’s artisans otherwise idled during COVID-19, our introductory course, CS50, had an unusual opportunity to collaborate with the same. Albeit subject to rigorous protocols, including face masks and face shields for all but the course’s instructor, along with significant social distancing, that moment in time allowed us an opportunity to experiment with lights, cameras, and action on an actual stage, bringing computer science to life in ways not traditionally possible in the course’s own classroom. Equipped with an actual prop shop in back, the team of artisans was able to actualize ideas that might otherwise only exist in slides and code. And students’ experience proved the better for it, with a supermajority of students attesting at term’s end to the efficacy of almost all of the semester’s demonstrations. We present in this work the design and implementation of the course’s theatricality along with the motivation therefor and results thereof. And we discuss how we have adapted, and others can adapt, these same moments more modestly in healthier times to more traditional classrooms, large and small.

CCS CONCEPTS
- Social and professional topics → Computational thinking:
  - CS1: Computer science education.

KEYWORDS
- analogies, demonstrations, demos, memorable moments, metaphors, pedagogy, props, sets, teachable moments

ACM Reference Format:
With that said, theatricality does not require an actual theater. (Though it did make it more fun, during that first year of COVID-19 especially.) Indeed, some of our demonstrations that year were simply higher-end alternatives to homemade equivalents that we ourselves had made in years past, often with paper and tape. We present in this work our repertoire of theatrical demonstrations, each of which is designed not only to introduce some concept but memorably so. Each analogy and metaphor aims to allow students to use what they already know to understand some new subject [6–8], particularly one that might be outside their own comfort zone. Our own analogies and metaphors tend to be higher-level than those of Waguespack [11], which focus more on programming primitives. Ours tend to be more algorithmic, too, simpler than those of Forišek and Steinová [2] but with some overlap in domains studied by Sanford et al. [9].

For us, this work was an opportunity to reflect on how and why we do what we do, particularly when we don’t have a whole theater ahead, we emphasize the latter versions herein, to facilitate adoption and adaptation by others. Achieved in this manner, our demonstrations themselves undoubtedly originated and inspired by our own teachers and colleagues. Italicized throughout are the key concepts introduced.

2.1 Tearing a phone book to explain binary search

The course’s first, and perhaps most memorable, moment, is meant to introduce students to algorithms by way of a phone book with hundreds of pages. (We estimate 1,024 sheets.) We ask students rhetorically how we might find “David;” for instance, in that phone book, assuming it’s sorted (for the sake of discussion) by first name. We proceed immediately to search for him from the first page toward the last, one sheet at a time. We pause after a few page turns to ask whether the algorithm is correct. We confirm that it is, because if David is in the phone book, we’ll eventually reach him. We then ask whether the algorithm is efficient. We admit that it isn’t, because if he (or whoever we’re calling) is toward the end, it might take us nearly a thousand steps to reach. We then restart the search, this time flipping two sheets at a time. We again ask whether the algorithm is correct. It now isn’t, because David might end up “sandwiched” between two sheets. We explain there’s a bug. We ask whether the bug is fixable. We acknowledge that, if we find that we’re alphabetically beyond David, we can just double-back one or a few pages. Whereas the first algorithm might take as many as one thousand steps, we explain, the second algorithm might take only five hundred, give or take.

We ask how students themselves might search the same phone book. We posit that most would open the phone book to, roughly, its middle. We demonstrate such and claim that we’re in the “M” section. We ask what we now know about the pages to the left and to the right of that section. We confirm that David must be to the left. We dramatically tear the phone book in half (down the spine) and throw (the right) half of the problem away. We continue to divide and conquer just as dramatically until we’re left with one sheet. We ask how many steps that third algorithm might take. We confirm roughly ten (i.e., $\log_2 1,024$). We pretend to call David. We assure students that they have the intuition already to be successful in computer science.

We then give the first two algorithms a name, linear search, likening them to searching along a line, from left to right, albeit at different rates. We then give the third algorithm a name, binary search, noting that a prefix of “bi” implies two, just as we split the phone book in two. We emphasize just how much faster that third algorithm is: if the phone book were to double in size, the first algorithm might take one thousand more steps, the second algorithm might take five hundred more, but the third algorithm would take only one more. We present Figure 2, explaining that the third algorithm takes not linear but logarithmic time.

We translate the algorithm to pseudocode, introducing verbs as functions, decisions as conditionals with Boolean expressions, and repetitions as loops.

2.1.1 Discussion. Not only do 88% of students report this moment to be helpful, per Figure 1, students anecdotally report this moment to be the course’s most memorable as well, even years later. The demonstration is not without pitfalls, though. If we start by asking...
At term’s end, the course’s 700 students were asked to evaluate the course’s demonstrations. A majority of students found more than half of the demonstrations “very helpful.” And a majority of students found all of the demonstrations “very helpful” or “somewhat helpful.”

We introduce students to algorithms in the course’s first lecture, including high-level previews of linear search and binary search. Depicted here is the time required to search a phone book, using linear search (one or two sheets at a time) or binary search, as a function of the size, $n$, of the phone book.

students how we could search for David, instead of diving immediately into a linear search ourselves, someone invariably shouts that we should use binary search, using terminology that most of their classmates would not yet know. When asked whether our first algorithm is correct, students frequently answer no, conflating inefficiency with incorrectness, though that itself is a teachable moment. When asked how else to search for David, students frequently propose starting with the “D” section, sometimes assuming incorrectly that the phone book has an index along its edge (which, admittedly, some do), sometimes not realizing that finding that, would itself, take some number of steps. As for the demonstrations themselves, it’s physically difficult to flip two sheets at a time at a uniform speed, to convey that it’s (theoretically) twice as fast as just one. It’s easier to find thick (commercial) yellow pages than (residential) white pages, so we tend to pretend that David is in yellow. Though it’s increasingly difficult to find any phone books at all. And, as of 2021, at least one student reported not knowing what a phone book even is. Though we now present a screenshot of a mobile phone’s contacts, to liken our search to now-familiar autocomplete.

2.2 Opening doors to explain linear and binary search

We later revisit linear and binary search at a lower level. We erect an array of seven doors in standalone door frames on stage, all of them closed, side by side. Hiding behind each is a different life-sized number (some with fur, some with googly eyes). We invite a volunteer to try to find a particular number. We emphasize that the doors are closed so that they must methodically index into them, opening one at a time. Once the student finds the number, we ask them to explain what their algorithm was.

We then close all the doors, rearranging the numbers behind them, this time arranging them in ascending order, left to right. We invite another volunteer to find a different number, disclosing that the numbers are now sorted. Once the student finds the number, we ask them to explain what their algorithm was and how the added assumption helped them, if it did.

2.2.1 Discussion. 86% of students find this demonstration helpful, per Figure 1. Though this demonstration is certainly possible without all the doors. Without the luxury of a prop shop, we sometimes cart with us seven small lockers instead (which could alternatively be those in a hallway for small classes). And in smaller classrooms, we typically use seven sheets of paper taped to a blackboard, with numbers written in chalk behind them. For the first volunteer, we
find it helpful to select a small number like 0, hidden behind the rightmost door, as many students start from the left and move right, thereby demonstrating that linear search is in $O(n)$. Some students open doors randomly and even get lucky, finding the number immediately by chance. Hilarity tends to ensue, all the more memorably, if suboptimally, for a discussion of $O$, but opportunely for a discussion of $\Omega$ as well. Almost all volunteers decide to apply binary search to the second set of doors, so we find it helpful to prescribe a number that we expect will be behind the last door they open. We always use seven doors so that each subset has a well-defined middle, without rounding. We daresay that fifteen or more might be better for more repetition but might be unwieldy to set up. Ideally, we use a different set of numbers for each search (one unordered, one ordered), lest students remember the first search’s numbers and deduce, in constant time, where some sorted number will be.

2.3 Plastic numbers to explain sorting

But how much time does it take to sort those numbers before we can use binary search? To introduce students to comparison sorts, we place an array of eight plastic numbers (each of which lights up with a switch) on a table or shelf, initially unsorted. We ask a volunteer to come up and sort them in ascending order. We then ask the volunteer what their algorithm was. Invariably, they describe some variant (or amalgam) of selection sort and bubble sort, though not by name.

We then reset the numbers to their original, unsorted positions. We propose to sort the array by selecting the smallest number first. We emphasize that we must step through the array, left to right, to determine which number is smallest; we can’t decide, at a glance all at once, like the audience can. (We don’t bother with closed doors, for time’s sake.) As we step through the array (literally, walking a step at a time, left to right), we make clear that we’re making mental note, as with a variable, of the index of the smallest number we’ve seen yet. Once at the end of the array, we pick up the number at that index and ask students where we should put it instead. A student invariably proposes to put it at the beginning. We remind them that we can’t just make room for it there on the edge of the table or shelf; the array has a fixed length. A student typically proposes that we shift everything to the right, in which case we respond that it seems like a lot of unnecessary work. We counter-propose swapping the smallest number with the leftmost number. After all, if the latter was there randomly anyway, we’re not necessarily making the problem any worse. We then light up that smallest number, now in its final location. And we repeat for the next-smallest numbers in turn. We observe that the whole list is sorted once all numbers are lit. We reveal the algorithm’s name to be selection sort. And we demonstrate it once more, this time using a digital animation [3] with vertical bars of short and tall heights representing small and large numbers, respectively, to make the selection of each smallest number more visually clear. We conclude with an analysis of our total number of steps. We observe that our search for the smallest number took $n$ steps (or $n - 1$ comparisons); our search for the next-smallest took $n - 1$ steps; and so forth. We ask students to trust us that the sum thereof is $(n^2 + n)/2$, which is in $O(n^2)$. We explain why the algorithm, as defined, is also in $\Omega(n^2)$ and, in turn, $\Theta(n^2)$.

We then reset the numbers again. We propose to do better. We ask students to explain in what sense the array is unsorted. A student typically cites an example of two (adjacent) numbers that are out of order. We proceed to swap the two numbers, followed by any other such pairs, left to right, again and again. As larger numbers “bubble” their way toward the end of the list, we light them up once in their rightmost positions. We again observe that the whole list is sorted once all numbers are lit. We reveal the algorithm’s name to be bubble sort. We demonstrate it once more, again using digital animation to make the pairwise swapping and bubbling more clear. And we again analyze our number of steps, comparing $n - 1$ pairs of numbers as many as $n - 1$ times, totaling $(n - 1)^2$ steps, which is again in $O(n^2)$. But we note that, if we short-circuit this algorithm after a pass with no swaps, we can achieve $\Omega(n)$ this time instead.

We reset the numbers one final time, ideally on a shelf with one or more empty shelves below (representing additional space). We then introduce students to merge sort by way of pseudocode, which we then enact, merging sorted halves from one shelf to another. We explain why merge sort is in $\Theta(n \log n)$. We conclude class itself with a digital animation showing selection sort, bubble sort, and merge sort in parallel, with the last dramatically finishing an order of magnitude faster [1].

2.3.1 Discussion. 85% of students find these moments helpful as well, per Figure 1. But we have learned not to leave too much of the narrative to chance, as by asking too many questions. On occasion, students have responded with algorithmic suggestions that don’t quite map to the algorithms (and order thereof) that we hope to discuss. Pedagogically, we prefer the progression from good, to better, and to best, asymptotically speaking. More so than other demonstrations, then, we tend to steer this one’s narrative. These algorithms’ enactments can be messy as well without practice, as it’s all too easy to stand in front of the numbers you’re swapping or merging, blocking students’ own view. (And standing behind the numbers instead otherwise involves doing everything backwards.) When lacking for shelf space, we sometimes have students hold the numbers themselves (or printouts thereof) and implement selection sort and bubble sort physically, which tends to be fun but less visually clear. The digital animations are good supplements, though, as they present the same algorithms graphically, at a uniform pace.

2.4 Glasses of water to explain swapping variables

To help students understand and implement in-place sorting algorithms (or swap values more generally), we take out two glasses of water, each colored differently via drops of food coloring. (We’ve used milk and orange juice too.) We explain that each glass represents a variable, with the colored water therein its value. (By this point in the course, students have used variables to store values but not necessarily swap.) We ask for a student to volunteer to swap the two liquids, somehow pouring the water from one glass into the other and vice versa. The volunteer typically hesitates, at which point we offer them an empty glass as a temporary variable with which to perform the swap in three steps. We then translate the steps to three lines of code for which students then have a mental model.
2.4.1 Discussion. Per Figure 1, 83% of students find this demonstration helpful, whereby those same lines of code seem to fail if implemented within a function, in which the swap is local. We then introduce pointers as a solution thereto, passing by reference rather than passing by value. Among more comfortable students, we sometimes demonstrate how to swap values without a temporary variable using bitwise XOR operations instead. We have even tried to enact such (using just two glasses) with water and oil, which theoretically don’t mix, but not visibly enough for a good metaphor. On at least one occasion, too, when asked to swap two liquids (without an empty glass), a student simply swapped the positions of the two glasses, so we have since clarified our instruction.

2.5 Mailboxes to explain pointers
To help students understand memory and pointers during our first several weeks in C, we have long drawn pictures with arrows. More helpful, perhaps, has been a pair of traditional mailboxes (on posts) that we picked up from Home Depot. One has a name, P, clearly labeled as such with a sticker, akin to a family’s name on a mailbox. When we open that mailbox, we find a value, a sheet of paper where we point using an oversized foam finger (as you might find in a stadium). Inside of that mailbox is a (non-pointer) value or, better yet, treasure.

2.5.1 Discussion. 83% of students find this demonstration helpful, per Figure 1. Better still, though, might be a whole wall of mailboxes, as you might find in an apartment instead, which would resemble a bank of memory more closely, albeit more challenging to set up.

2.6 Wooden blocks to explain linked lists
To help students visualize the data structures that they can then build with those pointers, we build a linked list of students on stage. We malloc one student at a time, asking each volunteer to represent a node, holding some value in one hand and a foam finger in the other, pointing at the next node in the list (or at the floor if NULL). We emphasize that the nodes need not be contiguous in memory; we deliberately spread volunteers out. And we ask the audience how we might insert additional nodes at the start, end, and middle of the list, enacting each in turn. Invariably, some nodes are accidentally orphaned during insertions, at which point we discuss memory leaks too.

2.6.1 Discussion. 79% of students find this demonstration helpful as well, per Figure 1. With no students in person during COVID-19, though, we temporarily replaced volunteers with large wooden blocks, built by the prop shop to represent nodes, each connected to another via an orange extension cord and (unpowered) receptacle. Though we underappreciated just how heavy 3-feet-tall wooden blocks would be to move on stage, an accidental metaphor, perhaps, for how difficult memory can be to manage.

2.7 Refrigerator and milk to explain race conditions
Toward term’s end, we introduce students to real-world issues in computing like race conditions in the context of databases and SQL. Specifically, we invite students to consider what could go wrong if two users happen to “like” the most-liked egg on Instagram [4] at the same time, if updating that post’s counter isn’t atomic. And we enact that same issue with an old-time refrigerator on stage. We propose that one roommate arrives home to discover the refrigerator out of milk. And so they head out to buy more. In the meantime, another roommate returns home, only to discover the same. They, too, head out to buy more (without crossing paths with the other). The end result is more milk than they can both drink before it goes sour. We observe that the problem arises because, after one roommate makes a decision based on the state of the refrigerator, itself a variable of sorts, the other roommate makes a similar decision while that variable’s value is in the midst of an update. We ask students how to prevent such a “race.” Often, a student proposes that the first roommate leave a note. We counter-propose, more dramatically, that they instead lock the refrigerator outright (as with a chain and padlock we have on stage), unlocking it only once the value is updated. We then mention finer-grained transactions as well.

2.7.1 Discussion. 83% of students report this demonstration to be helpful, per Figure 1. The need for a refrigerator, though, limits its reenactment. We ourselves sometimes resort to a verbal narration instead, an oral allegory of sorts [5], or to a plastic miniature thereof.

3 FUTURE WORK
We present more succinctly in this section the demonstrations that fewer than half of students found “very helpful,” per Figure 1. (See Appendix for videos thereof.) A majority of students still found them, at least, “somewhat helpful,” so we plan to solicit additional feedback in future terms in order to refine or rethink each.

3.1 Light bulbs to explain binary
We first introduce introduce students to binary by way of light bulbs, each of which has a battery as well as a switch, akin to a transistor. We start with just one such bit, to represent 0 and 1. We then upgrade to three, to count in (unsigned) binary from 0 to 7. We later point out, after introducing Unicode, that the 64 light bulbs along the edge of the theater’s own stage might actually be encoding a message (e.g., HI MOM). We suspect we might be spending too much time on this “bit.”

3.2 Grid of tiles to explain memory
Thanks to the theater’s prop shop, we have an 8-by-8 grid of wooden tiles that represents a bank of memory, with each tile a byte. The tiles are dry erase-friendly, allowing us to draw values atop them. Beneath each tile is an icon of Oscar the Grouch representing a garbage value as well. We use the grid to depict stack frames especially, to clarify why swapping two values inside in a function has no effect on the caller’s copies thereof (i.e., other tiles), unless the values are passed in by reference. Moving the (magnetic) tiles tends to be clumsy, though, so we suspect we can improve this demonstration through more practice or digitization thereof.
3.3 Buckets of cards to explain hash tables
When discussing hash tables in the context of data structures, we introduce students to hashing by way of oversized playing cards, hashing each card into one of four buckets (also from Home Depot) according to its suit. Because this particular demonstration only indirectly relates to how we later hash strings into actual hash tables, we might replace this one altogether.

3.4 Stacking bricks to explain recursion
When discussing recursion, we observe that a pyramid of “bricks” from Super Mario Bros. is itself a recursive structure whereby a pyramid of height $n$ is but a pyramid of height $n-1$ plus another layer of bricks. Because of gravity, though, it’s difficult to build such (with cardboard blocks) on stage, as by lifting $n-1$ layers to add the other. We might revert to presenting this structure graphically.

3.5 Phone calls to explain callback functions
When surveying paradigms in other languages at term’s end, we introduce students to asynchronous functions and callbacks in JavaScript by calling a colleague during class on the phone. Upon picking up, they explain that they’ll need to call us back with the answer to some question. Class is later interrupted with an asynchronous callback. We spend relatively little time on JavaScript itself, so we suspect the returns of this demonstration are simply low in terms of opportunities for application thereof.

3.6 Black box to explain functions
When first introducing students to functions, we take out an actual black box, inserting into it one or more inputs (e.g., two slips of paper with numbers) and taking out some output (e.g., another slip of paper, prepared in advance with the sum of those numbers). We explain that we don’t (need to) know how the box works inside; its implementation details are, for now, abstracted away. Insofar as we have tended to present this demonstration before implementing actual functions with code, we suspect it’s not obvious during the demonstration itself what we are actually abstracting away. We might try presenting it afterward instead, so that it’s clearer in retrospect what the abstraction represents.

4 RESULTS
When asked at term’s end what they thought of the course’s use of physical props during lectures to help explain topics, nearly all students reported loving (65%) or liking (27%) the same, per Figure 3. They were “engaging” and “fun,” reported some students. “It really helped me understand at a different level and helped me remember the material better,” reported one student. And “they made me comprehend something instead of just recalling it,” explained another. “It helped to visualize all of the code and ideas that would otherwise just be letters, symbols, numbers, and indents,” elaborated another.

That said, not all students felt the same, with time spent a concern. For instance, one found that “they were often unnecessary. Helpful, but unnecessary. For me, an animated diagram on the slides would have been sufficient, and often felt that these demonstrations took up much more time than necessary.” Another distinguished between engagement and learning: “I liked them because they were engaging, but I don’t think they helped a lot with my learning.” But engagement did recur as a theme: “it really helped me stay engaged, especially in the virtual nature of this semester.” And as another student acknowledged, “I don’t really get value from stuff like that but I know it helps others.”

To be fair, we have not run a controlled experiment, creating memorable moments for some students but not others. Nor have we ourselves tracked students’ performance beyond course’s end. But that so many students reported those moments as still memorable at course’s end is encouraging for long-term retention and comfort as students move on to higher-level courses next with those foundations in place. And we do plan to reduce time spent on some demonstrations in order to strike a better balance.

5 CONCLUSION
CS50’s flair for theatricality predates COVID-19 itself. But a silver lining of that particular moment in time was an opportunity for us to collaborate with a team of artisans to bring computer science all the more to life on a stage, for an audience, no less, that could not be there in person. The collaboration, too, proved an opportunity for us to reflect on how we might introduce students more effectively to that which is not familiar by way of that which already is, via analogies, metaphors, and theatrical props. Ultimately, the collaboration did not enable pedagogical techniques that aren’t already available to us and others off-stage as well, equipped as we more often are with just paper and tape. But it did come at just the right time for so many students who were otherwise isolated at home.

APPENDIX
See https://www.youtube.com/cs50 for videos of every demonstration herein.

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REFERENCES


