<u>World Computer Project – Preliminary Research Findings</u>

Project description: the aim of this project is to build a device that contains no major hardware components, including, but not limited to, storage, memory, CPUs, and GPUs. Instead, all of the computationally intensive tasks are offloaded to fully rigged computers, and are only done so *on-demand*. The anticipated benefits of this model are:

- *Reduction in the cost of user-end devices*. The logic behind this stems from the fact that even when users' computers are powered on, most of their computational resources are sitting idle most of the time. In our case, computational resources never sit idle – computation is provided and payed for *on-demand*.
- *A more varied, flexible, and powerful array of display technologies*. Displays are one of the most actively developed technologies on consumer markets today. However, it is sometimes difficult to integrate these advancements into users' devices. With much of the internal hardware out of the way, however, it becomes easier for consumer devices to make use of technologies such as flexible OLEDS, smart glasses (which are usually thick and clunky), and bionic contact lenses.
- *Limitless performance*. If well managed, users should never have their performance bottle-necked by limiting hardware components. If a user needs more computational resources to carry out their tasks without performance losses, they will get it. This provides for a better and more consistent user-experience.
- *Contiguous performance across all form factors.* All user-end devices, no matter the size or form of its display, can tap into the same levels of computational resources, since none of that hardware is located internally within the devices themselves. Today, larger devices with larger displays can afford to pack in more powerful hardware components, while smaller devices with smaller displays cannot. This places limits on the use-cases that are made available across different device form factors.
- *Contiguous user-experience and interfaces across all form factors.* Since all of the computation is done and managed externally, over time users can set up hardware and software profiles across all of their devices. Again, since the computational capacity across each device does not vary, all devices can afford to run the same set of software applications. This makes user-experiences between devices more contiguous.
- *Reduced power requirements and longer battery life*. This allows for the further development of technologies where power requirements are an issue (see bionic contact lens).
- *Limitless device life-cycles.* Because it is no longer users' responsibilities to maintain and upgrade their hardware, their devices can, in theory, be used forever. The incentive to upgrade their devices comes from the introduction of newer and more advanced displays, cameras, etc. If users happen to damage their devices, replacement costs will be cheaper (refer to first point).
- *Reduction of electronic waste*. If the entity buying and managing the actual computers/worker nodes is a corporation, they might be more incentivized to recycle their hardware components than consumers are.

The purpose of this report is to test the technical limitations of this technology, see if it is economically viable, and challenge the assumptions made above. In the aim of these pursuits, we must approach the problem from multiple perspectives, and cover topics such as: the anticipated cuts to a product's bill of materials, the freeing up of a device's internal space, and estimates of bandwidth, associated costs, and minimum latency requirements.

Model diagram:

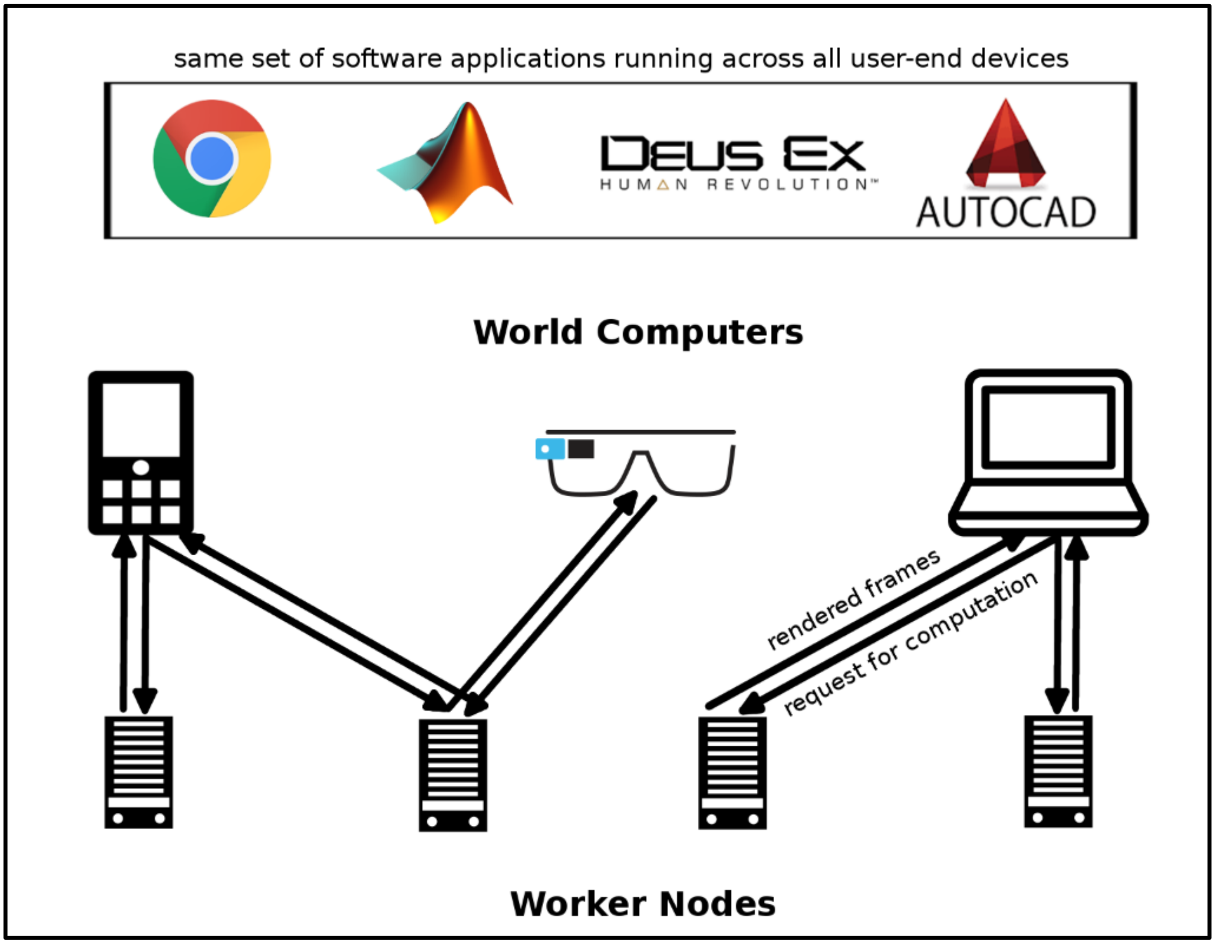

Figure 1: Model diagram showing the communication pathways between world computers (user-end devices) and a distributed network of worker nodes. Where a single user-end device opens up communication channels to multiple worker nodes at a time, a task is being run in parallel.

Anticipated Cuts to Bill of Materials:

At a minimum, we intend to remove all storage components, memory, central processing units, and graphical processing units from a device's bill of materials.

Smartphones:

Table 1: Bill of materials costs across commercial smartphones launched from the years 2010 to 2018. Note that an applications processor is more often than not a systems on a chip (SoC) that has onboard both a CPU and a GPU.

Year	Name	% of BOM (Storage + Memory + Applications Processor)	Link
2010	BlackBerry Torch 9800 12GB	24.4*	1
2010	HTC Droid 12GB	27.8*	2
2010	iPhone 4 16GB	27.9	3
2011	iPhone 4s 16GB, 32GB, 64GB	31.5**	4
2012	Samsung Galaxy S3 HSPA Version 16GB	22.6	5
2012	iPhone 5 16GB, 32GB, 64GB	24.3**	6
2013	Samsung Galaxy S4 LTE Version 16GB	20.6	5
2013	Samsung Galaxy S4 HSPA Version 16GB	24.6	5
2013	iPhone 5s 16GB, 32GB, 64GB	24.4**	7
2014	iPhone 6 16GB	17.8	8
2014	iPhone 6 Plus 16GB	16.6	8
2015	Samsung Galaxy S6 Edge 64GB	28.8	9
2015	iPhone 6s 16GB	20.6	10
2015	iPhone 6s Plus 16GB	19.2	10
2016	Samsung Galaxy S7 32GB	25*	11
2016	iPhone 7 32GB	19.7	12
2016	iPhone 7 Plus 32GB	16	14
2017	Samsung Galaxy S8 64GB	21.25	13
2017	iPhone 8 64GB	23.7*	14
2017	iPhone 8 Plus 64GB	20.6	15
2018	Samsung Galaxy S9+ 64GB	24.1*	16
2018	iPhone X 64GB	16.4	17
2018	iPhone Xs Max 64GB	18.1	18

*processing unit includes broadband IC in listed percentage value. Value is divided by two (based off my observations, percentage value of broadband IC was at most equal to that of the apps processor)

**averaged across all storage options

From this data set, we can conclude that at least 16.0-32.5% of total BOM costs can be cut, with the mean value placed at 22.4%. It can be argued that additional cuts are possible due to the presence of fewer/smaller mechanical enclosures. The images below shows an iPhone 8 with all its parts enclosed (left) and its motherboard (right). The motherboard occupies a little more than 30% of the phone's internal space. **By extension, by removing the motherboard and its components, more than 30% of space is freed up from our device's internals. It can be argued that even more space can be freed up due to a**

smaller battery, which occupies around 50% of the device's internal space. Again, this is made possible due to the device's power requirements being substantially reduced.

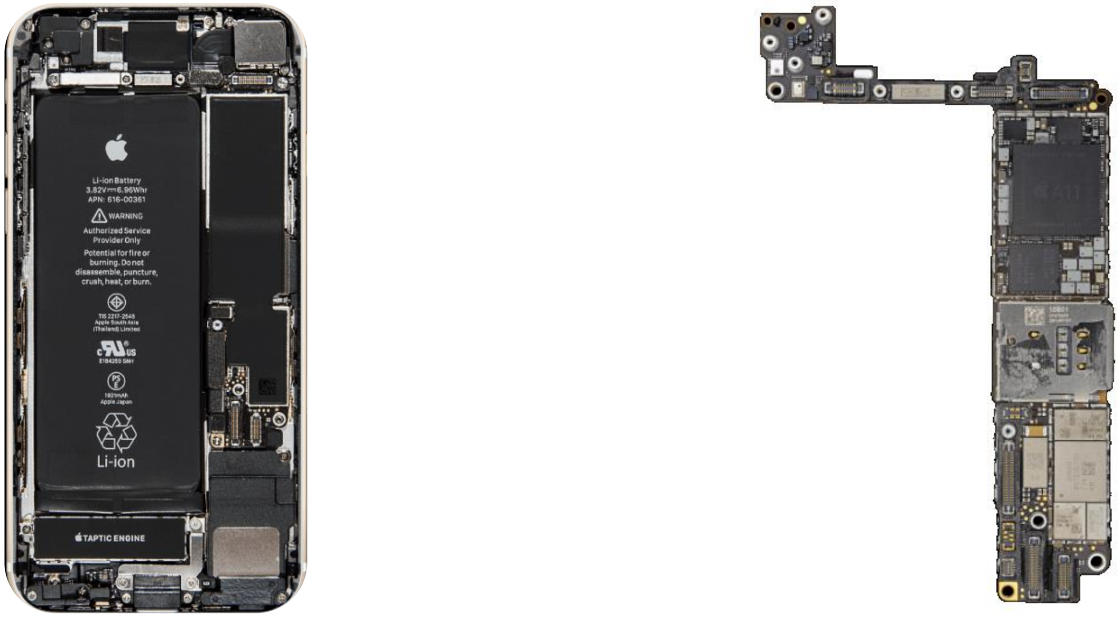

Figure 2: iPhone 8 internals (left) and iPhone 8 motherboard (right) containing apps processor, memory, and storage units

It should be noted that the approach taken in estimating percentage cuts to a smartphone's overall BOM is quite rudimentary. First and foremost, our dataset is limited. In addition, the approach does not take into account the depreciating costs of memory and storage over time. The figure below plots the values listed in Table 1, and shows how these values appear to decrease with time.

Figure 3: percentage cuts to BOM after removing apps processor, memory, and storage units from devices launched in the years 2010 through to 2018

In light of this fact, it might be appropriate to shorten our timescale. The figure below displays the same information as the figure above, but without data for the years of 2010 and 2011. The rate of change of the trend-line is lowered significantly, however the trend is still downward.

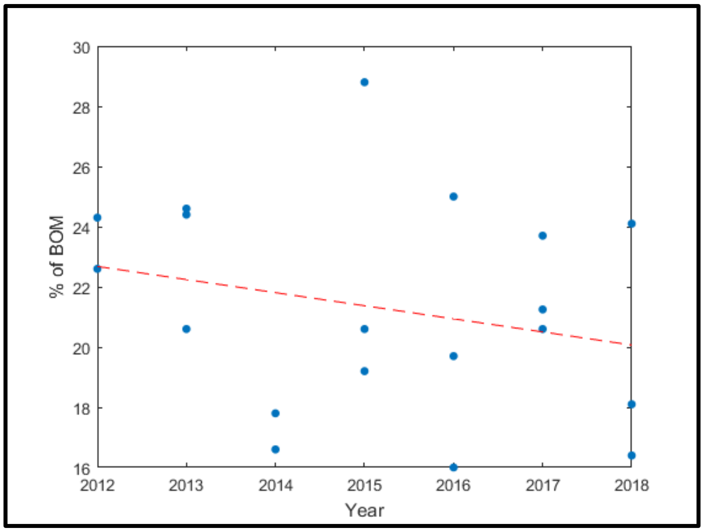

Figure 4: percentage cuts to BOM after removing apps processor, memory, and storage units from devices launched from the years 2012 through to 2018

Thus, the percentage cut to BOM figures highlighted above are most likely an overestimate. Despite this, I believe that making any predictions on how these figures will change going into the future is extremely difficult and premature, as in-depth market analyses are required. Furthermore, it is difficult to accurately judge how the effects of depreciating costs of hardware components holds up against the effects of increasing demand for use-cases that require higher-performing hardware.

Laptops/Desktops:

Unfortunately, bill of materials resources for laptop and desktop consumer products are lacking. However, research done by Barclay's Investment Bank in 2012 has produced the following figures [19]:

Table 2: Bill of materials costs for CPU, GPU, storage, and memory components in both desktops and laptops

	% of BOM (Storage)	% of BOM (Memory)	% of BOM (CPU)	% of BOM (GPU)*
Desktops	12-14	3-4	11-22	11-22
Laptops	11-12	2-3	11-28	11-28

*The only component not accounted for in this study is the GPU. GPUs typically cost more than CPUs, due to them containing both onboard memory and cooling systems. However, we will make the conservative assumption and equate the percentage values of GPUs with that of CPUs.

From Table 2, total BOM savings can be said to range anywhere from 47-62% for desktops and 35-71% for laptops. Substantial cuts can probably also be made to all mechanical enclosures and power supply units (more so than smartphones). When compared to smartphones, I anticipate more space to made available within the internals of desktops/laptops, since a significant amount of space is usually reserved for the purpose of proper ventilation of the major components, which are no longer in our devices. In addition, batteries can be made smaller due to reduced power requirements.

Estimated Bandwidth, Associated Costs, and Minimum Latency Requirements:

As is shown in Figure 1, worker nodes take the bitmaps of each frame that are stored in their GPUs' memory buffers and output that information to the world computers as byte streams. The amount of information contained within a bitmap can be calculated given the bitmap/image dimensions (N x M) and the color depth in bits (B) [20]. For consumer usage, the standard *must* be true-color, 24 bit RGB. Given this standard, our bitmap will contain **24 bits of information per pixel**. The amount of information contained within each frame is now dependent on the total number of pixels contained within the display. Given RAW data (no compression), we can measure the size of a frame for different native resolutions:

Table 3: Amount of information contained within each frame of devices released within the past two to three years

Pixel resolution	Size of a frame (Gbits/frame)
1334x750 (iPhone 7,8)	0.024012
1440x900 (MacBook Air)	0.031104
1792x828 (iPhone Xr)	0.035611
1920x1080 (iPhone 7,8 Plus, iMac (non-retina, 21.5"))	0.049766
2436x1125 (iPhone Xs)	0.065772
2048x1536 (iPad mini 4, iPad)	0.075497
2304x1440 (MacBook)	0.079626
2688x1242 (iPhone Xs Max)	0.080124
2224x1668 (iPad Pro, 10.5")	0.089031
2560x1600 (MacBook Pro 13")	0.098304
2880x1800 (MacBook Pro 15", iMac Pro)	0.124416
2732x2048 (iPad Pro, 12.9")	0.134283
4096x2304 (iMac 21.5", 4K Retina display)	0.226492
5120x2880 (iMac 27", 5K display)	0.353894

The bandwidth over the network depends on the number of times user-end devices need to refresh their frames (i.e. it depends on the frame rate). The appropriate frame rate depends, in turn, on our desired use-case (applications such as gaming and video streaming, for example, require higher frame rates than do most other applications). **At 60, 30, and 15 frames per second, the maximum (theoretical) latencies are 16.666 ms, 33.333 ms, and 66.666 ms, respectively.** These values are almost certainly underestimates, due to the fact that applications must take the time to do background housekeeping. The Chrome browser, for example, generally requires the rendering pipeline to be completed in no more than 10 ms [21]. Given these latency requirements, we can calculate the bandwidth needed to achieve a specific framerate as the size of the frame divided by the time interval between each frame:

Table 4: Bandwidth over a network at 60, 30, and 15 frames per second and for specific pixel resolutions

Pixel resolution	Bandwidth @ 60 fps (Gbits)	Bandwidth @ 30 fps (Gbits)	Bandwidth @ 15 fps (Gbits)
1334x750	1.4407	0.7204	0.3602
1440x900	1.8662	0.9331	0.4666
1792x828	2.1366	1.0683	0.5342
1920x1080	2.9860	1.4930	0.7465
2436x1125	3.9463	1.9732	0.9866
2048x1536	4.5298	2.2649	1.1325
2304x1440	4.7776	2.3888	1.1944
2688x1242	4.8074	2.4037	1.2019
2224x1668	5.3419	2.6709	1.3355
2560x1600	5.8982	2.9491	1.4746
2880x1800	7.4650	3.7325	1.8662
2732x2048	8.0570	4.0285	2.0142
4096x2304	13.5895	6.7948	3.3974
5120x2880	21.2337	10.6168	5.3084

Therefore, for the pixel resolutions listed in Table 4, we can conclude that data transfer rates of approx. 1.44-21.23 Gbps, 0.72-10.62 Gbps, 0.36-5.31 Gbps are required to support 60, 30, and 15 fps frame rates, respectively. Keep in mind, however, that the listed values are almost certainly underestimates, due to latencies brought about by application housekeeping and the wireless communication technologies themselves. With that said, it is also important to note that these calculations were done using RAW data that has not been encoded and/or compressed. This would reduce overall bandwidths, but would present a series of complications (to be discussed in future revisions).

The only wireless communication devices that can support the bandwidths listed in Table 4 are those built under **5G standards**, which support data transfer rates of up to 10-20 Gbits/second [22]. Under these specifications, wireless communication devices that adhere to 5G standards can support all but one of the data transfer rates listed in Table 4. It is important to note that the specifications for 5G have not yet been made official, and that peak data rates for 5G technologies only hold under conditions of low mobility and/or use of high frequency radios, which consume a lot of power.

An important question that has yet to be answered: how much power will our 5G wireless communication devices draw at given operating frequencies? This points to the broader question of: how much should I charge users for bandwidth (minus additions to rack-space)?

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