# Floorplan: Spatial Layout in Memory Management Systems

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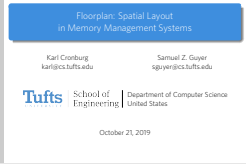
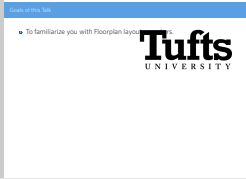


## Goals of this Talk

- To familiarize you with Floorplan layout operators.







Thank you. So to jump right in, after my time is up I hope you will be familiar with some key Floorplan layout operators. Floorplan is a DSL for describing the memory layout of a heap. Theeere's, a syntax: <slide>

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**Grammar 4:** Demarcatable atomic units of memory.

⟨*demarc-val*⟩ ::= (‘#’ | ⟨*formal-id*⟩)? (⟨*enum*⟩ | ⟨*bits*⟩ | ⟨*union*⟩ | ⟨*seq*⟩ | ⟨*ptr*⟩ | ⟨*size-arith*⟩ | ⟨*macro*⟩)

⟨*seq*⟩ ::= ‘`seq`’ ‘{’ ⟨*demarc*⟩ (‘,’ ⟨*demarc*⟩)* ‘,’? ‘}’

⟨*union*⟩ ::= ‘`union`’ ‘{’ ⟨*demarc*⟩ (‘|’ ⟨*demarc*⟩)* ‘|’? ‘}’

⟨*demarc*⟩ ::= ⟨*field*⟩ | ⟨*layer*⟩ | ⟨*demarc-val*⟩

⟨*field*⟩ ::= ⟨*field-id*⟩ ‘:’ ⟨*demarc-val*⟩

⟨*ptr*⟩ ::= (⟨*layer-id*⟩ | ⟨*field-id*⟩) ‘`ptr`’

⟨*enum*⟩ ::= ‘`enum`’ ‘{’ ⟨*flag-id*⟩ (‘|’ ⟨*flag-id*⟩)* ‘|’? ‘}’

⟨*bits*⟩ ::= ‘`bits`’ ‘{’ ⟨*bits-exp*⟩ (‘,’ ⟨*bits-exp*⟩)* ‘,’? ‘}’

⟨*bits-exp*⟩ ::= ⟨*field-id*⟩ ‘:’ ⟨*size-arith*⟩

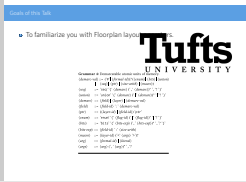
⟨*macro*⟩ ::= ⟨*layer-id*⟩ (‘<’ ⟨*args*⟩ ‘>’)?

⟨*arg*⟩ ::= ⟨*formal-id*⟩ | ⟨*literal*⟩

⟨*args*⟩ ::= ⟨*arg*⟩ (‘,’ ⟨*arg*⟩)* ‘,’?







which I will not get into the weeds about today. <slide>

## Goals of this Talk

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- To familiarize you with Floorplan layout operators.
- You want to read the paper to understand Floorplan mechanics.






Instead, I hope that you will, after today, want to go back and read the paper to better understand the mechanics of a Floorplan layout specification.
<slide>

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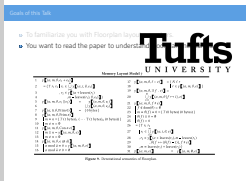
**Memory Layout Model $\bar{\gamma}$**

$$
\begin{array}{lll}
1 & \gamma[\![(\alpha, m, \theta, e_1 + e_2)]\!] & \\
2 & \quad = \{\, T\ r_1\ r_2 \mid r_1 \in \bigcup_{i=0}^{m} \gamma[\![(\alpha, i, \theta, e_1)]\!] & \\
3 & \qquad , r_2 \in \gamma[\![(\alpha + \text{leaves}(r_1)) & \\
4 & \qquad\quad , m - \text{leaves}(r_1), \theta, e_2)]\!] \,\} & \\
5 & \gamma[\![(\alpha, m, \theta, e_1 \parallel e_2)]\!] \quad = \quad \gamma[\![(\alpha, m, \theta, e_1)]\!] & \\
6 & \qquad\qquad\qquad\quad \bigcup \gamma[\![(\alpha, m, \theta, e_2)]\!] & \\
7 & \gamma[\![(\alpha, 0, \theta, \text{Prim } 0)]\!] \quad = \quad \{\, 0 \text{ bytes} \,\} & \\
8 & \gamma[\![(\alpha, m, \theta, \text{Prim } n)]\!] & \\
9 & \quad \mid m \equiv n = \{\, T\ (1 \text{ bytes})_1\ (\cdots\ T\ (1 \text{ bytes})_n\ (0 \text{ bytes})) \,\} & \\
10 & \quad \mid m \neq n = \emptyset & \\
11 & \gamma[\![(\alpha, m, \theta, \text{Con } n\ e)]\!] & \\
12 & \quad \mid m \equiv n = \gamma[\![(\alpha, m, \theta, e)]\!] & \\
13 & \quad \mid m \neq n = \emptyset & \\
14 & \gamma[\![(\alpha, m, \theta, \text{e } @\ \hat{a})]\!] & \\
15 & \quad \mid \alpha \bmod \hat{a} \equiv 0 = \gamma[\![(\alpha, m, \theta, e)]\!] & \\
16 & \quad \mid \alpha \bmod \hat{a} \neq 0 = \emptyset & \\
17 & \gamma[\![(\alpha, m, \theta, \ell :: e)]\!] \quad = \{\, N\ \ell\ r & \\
18 & \qquad\qquad\qquad\quad \mid r \in \gamma[\![(\alpha, m, \theta, e)]\!] \,\} & \\
19 & \gamma[\![(\alpha, m, \theta, \exists\ f\ .\ e)]\!] = & \\
20 & \qquad \bigcup_{i=0}^{m} \gamma[\![(\alpha, m, \theta\{f \mapsto i\}, e)]\!] & \\
21 & \gamma[\![(\alpha, m, \theta, f \neq e)]\!] & \\
22 & \quad \mid f \notin \text{dom}(\theta) = \emptyset & \\
23 & \quad \mid m \equiv \theta(f) \equiv 0 = \{\, T\ (0 \text{ bytes})\ (0 \text{ bytes}) \,\} & \\
24 & \quad \mid \theta(f) \equiv 0 = \emptyset & \\
25 & \quad \mid \theta(f) > 0 & \\
26 & \quad = \{\, T\ r_1\ r_2 & \\
27 & \qquad \mid r_1 \in \bigcup_{i=0}^{m} \gamma[\![(\alpha, i, \theta, e)]\!] & \\
28 & \qquad , r_2 \in \gamma[\![(\alpha + \text{leaves}(r_1), m - \text{leaves}(r_1) & \\
29 & \qquad\quad , \theta\{f \mapsto (\theta(f) - 1)\}, f \neq e)]\!] & \\
30 & \qquad , m \equiv \text{leaves}(r_1) + \text{leaves}(r_2) \,\} & \\
31 & \bar{\gamma}[\![(\alpha, m, e)]\!] \quad = \quad \gamma[\![(\alpha, m, \emptyset, e)]\!] &
\end{array}
$$

**Figure 9.** Denotational semantics of Floorplan.







Which, includes a denotational semantics defining what /is/ and /is not/ a valid heap instance, given a particular memory layout (as defined by a Floorplan specification).

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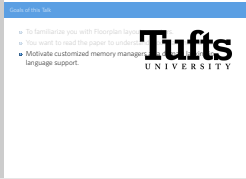
- Motivate customized memory managers as a domain lacking in language support.








Instead, I want to tell you how someone other than a runtime system developer, can benefit from implementing their own customized memory manager, and how Rust code <slide>

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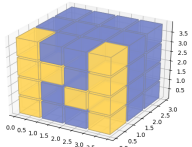

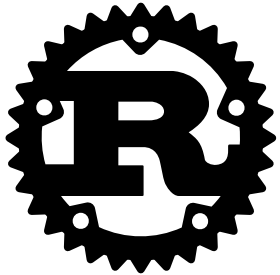





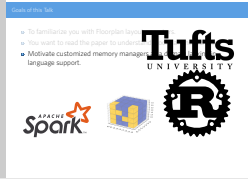

generated from a Floorplan specification fits into that picture, even while frameworks like Apache Spark, and libraries like NumPy make their own tradeoffs in the memory management design space. <slide>

## Goals of this Talk

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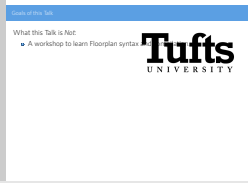
What this Talk is *Not*:

- A workshop to learn Floorplan syntax and compilation.








To be clear, <slide>

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$$\mathbb{C}[\![\ \langle \textit{layer-simple} \rangle\ ]\!] = \mathbb{C}[\![\ \langle \textit{layer-id} \rangle\ \text{`<'}\ \langle \textit{formals} \rangle\ \text{`>'})?\ \langle \textit{mag} \rangle?\ \langle \textit{align} \rangle?\ \text{`->'}\ \langle \textit{demarc-val} \rangle\ ]\!],\ f_i \in \langle \textit{formals} \rangle \quad \vdash \langle \textit{layer-id} \rangle :: (\exists\ f_0\ .\ \cdots \exists\ f_n\ .\ (\mathbb{M}[\![\ \langle \textit{mag} \rangle\ ]\!]\ (\mathbb{C}[\![\ \langle \textit{demarc-val} \rangle\ ]\!]\ @\ (\Delta_{\text{byte}}[\![\ \langle \textit{align} \rangle\ ]\!])))) \tag{1}$$

$$\mathbb{C}[\![\ \langle \textit{demarc-val} \rangle\ ]\!] = \mathbb{C}[\![\ \text{`\#'}\ \langle \textit{demarc-val} \rangle\ ]\!] \quad \vdash \text{let } f = \texttt{fresh}(\langle \textit{demarc-val} \rangle) \text{ in } \exists\ f\ .\ f\ \#\ \mathbb{C}[\![\ \langle \textit{demarc-val} \rangle\ ]\!] \tag{2}$$

$$\mathbb{C}[\![\ \langle \textit{demarc-val} \rangle\ ]\!] = \mathbb{C}[\![\ \langle \textit{formal-id} \rangle\ \langle \textit{demarc-val} \rangle\ ]\!] \quad \vdash \langle \textit{formal-id} \rangle\ \#\ \mathbb{C}[\![\ \langle \textit{demarc-val} \rangle\ ]\!] \tag{3}$$

$$\mathbb{C}[\![\ \langle \textit{seq} \rangle\ ]\!] = \mathbb{C}[\![\ \text{`seq'}\ \text{`\{'}\ \langle \textit{demarc} \rangle_0 \cdots \langle \textit{demarc} \rangle_n\ \text{`\}'}\ ]\!] \quad \vdash \mathbb{C}[\![\ \langle \textit{demarc} \rangle_0\ ]\!] + \cdots + \mathbb{C}[\![\ \langle \textit{demarc} \rangle_n\ ]\!] \tag{4}$$

$$\mathbb{C}[\![\ \langle \textit{union} \rangle\ ]\!] = \mathbb{C}[\![\ \text{`union'}\ \text{`\{'}\ \langle \textit{demarc} \rangle_0\ \text{`|'} \cdots \text{`|'}\ \langle \textit{demarc} \rangle_n\ \text{`\}'}\ ]\!] \quad \vdash \mathbb{C}[\![\ \langle \textit{demarc} \rangle_0\ ]\!] \,\|\cdots\|\, \mathbb{C}[\![\ \langle \textit{demarc} \rangle_n\ ]\!] \tag{5}$$

$$\mathbb{C}[\![\ \langle \textit{field} \rangle\ ]\!] = \mathbb{C}[\![\ \langle \textit{field-id} \rangle\ \text{`:'}\ \langle \textit{demarc-val} \rangle\ ]\!] \quad \vdash \langle \textit{field-id} \rangle :: \mathbb{C}[\![\ \langle \textit{demarc-val} \rangle\ ]\!] \tag{6}$$

$$\mathbb{C}[\![\ \langle \textit{ptr} \rangle\ ]\!] = \mathbb{C}[\![\ (\langle \textit{layer-id} \rangle \mid \langle \textit{field-id} \rangle)\ \texttt{`ptr'}\ ]\!] \quad \vdash \mathbb{C}[\![\ 1\ \text{word}\ ]\!] \tag{7}$$

$$\mathbb{C}[\![\ \langle \textit{enum} \rangle\ ]\!] = \mathbb{C}[\![\ \texttt{`enum'}\ \text{`\{'}\ \langle \textit{flag-id} \rangle_0 \cdots \langle \textit{flag-id} \rangle_n\ \text{`\}'}\ ]\!] \quad \vdash \text{Prim}\left\lceil \log_2(n+1) * \frac{1\ \text{byte}}{8\ \text{bits}} \right\rceil \tag{8}$$

$$\mathbb{C}[\![\ \langle \textit{bits} \rangle\ ]\!] = \mathbb{C}[\![\ \texttt{`bits'}\ \text{`\{'}\ \langle \textit{bits-exp} \rangle_0 \cdots \langle \textit{bits-exp} \rangle_n\ \text{`\}'}\ ]\!] \quad \vdash \text{Prim}\left\lceil \left( \sum_{i=0}^{n} (\Delta_{\text{bit}} \langle \textit{bits-exp} \rangle_i) \right) * \frac{1\ \text{byte}}{8\ \text{bits}} \right\rceil \tag{9}$$

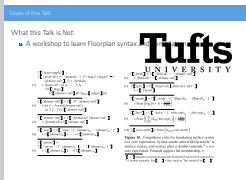
$$\mathbb{C}[\![\ \langle \textit{size-arith} \rangle\ ]\!] \vdash \text{Prim}\left(\Delta_{\text{byte}} \langle \textit{size-arith} \rangle\right) \tag{10}$$

**Figure 10.** Compilation rules for translating surface syntax to a core expression. Syntax inside oxford-like brackets[9] is surface syntax, and syntax after a double-turnstile[10] $\vdash$ is a core expression. Formals support list membership, $\in$.

[9] $[\![ \ldots ]\!]$ separates raised syntax (inside brackets) from lowered expressions.
[10] A double-turnstile, Foo $[\![ \ldots ]\!] \vdash$ Bar, reads as "Bar models Foo $[\![ \ldots ]\!]$".







there's a Floorplan compiler into a core calculus which you can find in the paper in Figure 10. <slide>

## Goals of this Talk

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What this Talk is *Not*:

- A workshop to learn Floorplan syntax and compilation.
- The paper. Examples are novel, Floorplan syntax herein matches paper.






The paper also discusses a general purpose memory manager <slide>

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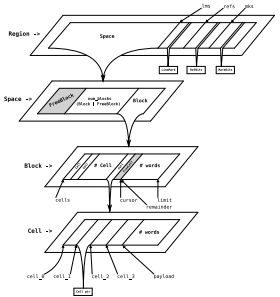
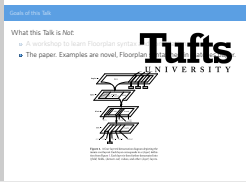



**Figure 4.** A four-layered demarcation diagram depicting the immix-rust layout. Each layer corresponds to a ⟨*layer*⟩ definition from Figure 5. Each layer is then further demarcated into ⟨*field*⟩ fields, ⟨*demarc-val*⟩ values, and other ⟨*layer*⟩ layers.







which I'm glad to answer questions about, but will not present today. <slide>

## Goals of this Talk

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What this Talk is *Not*:

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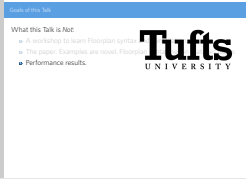
- The paper. Examples are novel, Floorplan syntax herein matches paper.
- Performance results.








And finally, I'm interested in language support with really good performance
<slide>

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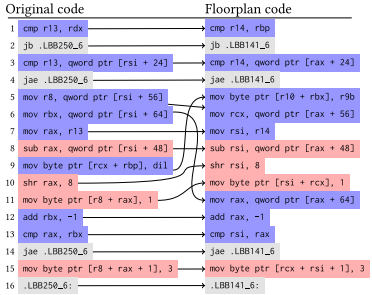
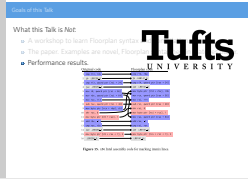



**Figure 15.** x86 Intel assembly code for marking immix lines.



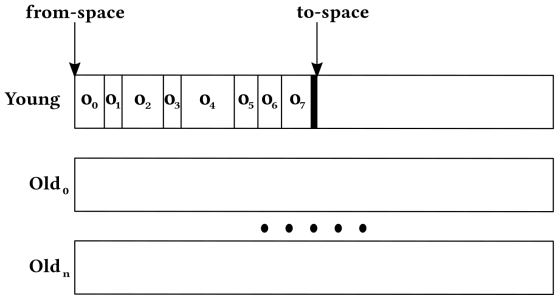




as discussed more in the paper with manual inspections of compiled assembly code. <2 slides> <2+ minutes here>

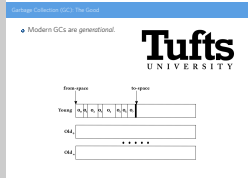
## Garbage Collection (GC): The Good

- Modern GCs are *generational*.





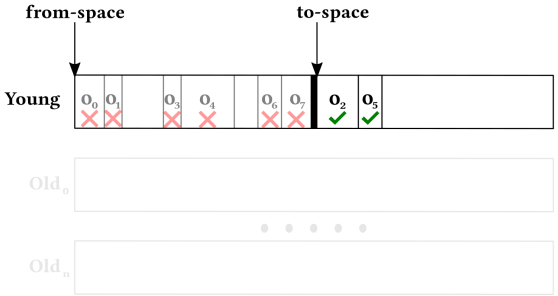


But a little background first. Modern garbage collectors typically achieve good performance by being generational. In a generational collector, heap objects are divided into regions of memory based on their age, where age is typically measured in the number of bytes allocated up until the current point of execution in the program. Aaaand down here in this depiction, we see 8 objects have been allocated into the young space, at which point a garbage collection is triggered because we've run out of allocatable space. <slide>

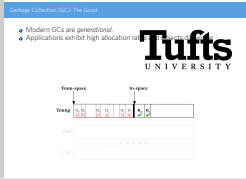
## Garbage Collection (GC): The Good

- Modern GCs are *generational*.
- Applications exhibit high allocation rates and objects die young





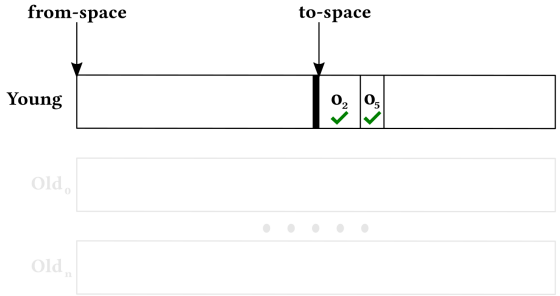


In the best case, our application will exhibit a high turnover rate, meaning most of the objects we allocated since the last GC will have died, and we only need to evacuate (that is, copy) a small number of objects into the evacuation region, <slide>

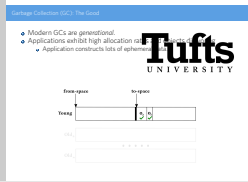
## Garbage Collection (GC): The Good

- Modern GCs are *generational*.
- Applications exhibit high allocation rates and objects die young
  - Application constructs lots of ephemeral data.





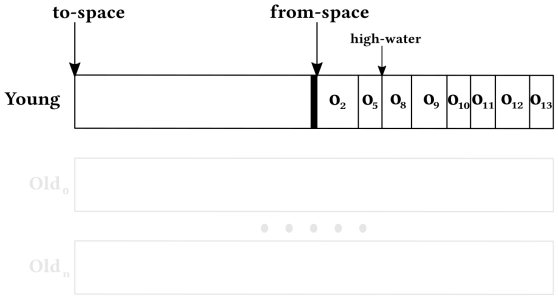


at which point we can resume allocation. <slide>

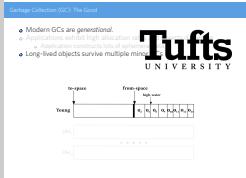
## Garbage Collection (GC): The Good

- Modern GCs are *generational*.
- Applications exhibit high allocation rates and objects die young
  - Application constructs lots of ephemeral data.
- Long-lived objects survive multiple minor GCs





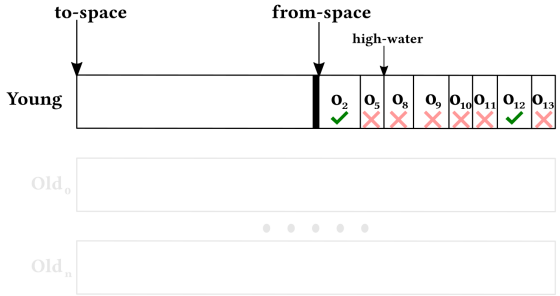


Over the time though, some objects will outlast multiple GCs, <slide>

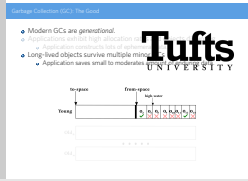
## Garbage Collection (GC): The Good

- Modern GCs are *generational*.
- Applications exhibit high allocation rates and objects die young
  - Application constructs lots of ephemeral data.
- Long-lived objects survive multiple minor GCs
  - Application saves small to moderates amount of enduring data.





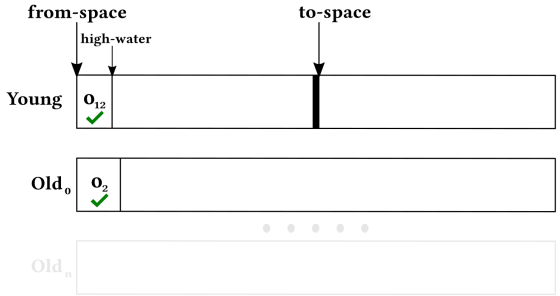


as is the case in the following example, where object O-two survives it's second GC in the young space. <slide>

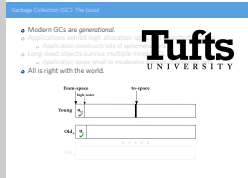
## Garbage Collection (GC): The Good

- Modern GCs are *generational*.
- Applications exhibit high allocation rates and objects die young
  - Application constructs lots of ephemeral data.
- Long-lived objects survive multiple minor GCs
  - Application saves small to moderates amount of enduring data.
- All is right with the world.







And, as a result, we copy O-two over into the first old generation. We do this, because we can perform garbage collection on the old generation less frequently than we do on the young generation, thus improving program runtime at the cost of some memory pressure. ... <look at slide> ... Aaaand, all is right with the world because performance is good, precisely because most applications exhibit this pattern. <2 slides>

## Garbage Collection: Motivating Custom Allocators

Tufts UNIVERSITY

- Performance is poor on non-generational and specialized workloads.





Garbage Collection: Motivating Custom Allocators
Tufts UNIVERSITY
- Performance is poor on non-generational and specialized workloads.

Except not always. On certain non-generational and specialized application workloads, we get performance degredation. <slide>

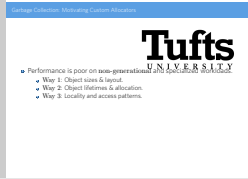
## Garbage Collection: Motivating Custom Allocators

Tufts UNIVERSITY

- Performance is poor on non-generational and specialized workloads.
  - Way 1: Object sizes & layout.
  - Way 2: Object lifetimes & allocation.
  - Way 3: Locality and access patterns.








So for the remainder of this talk, I plan to describe the following three characteristics of an application which can degrade performance of a generational garbage collector, and in doing so, show you how language support in the form of generated memory interfaces, can reduce the burden of implementing a customized memory manager for tackling these performance constraints. <slide> <5 minutes>

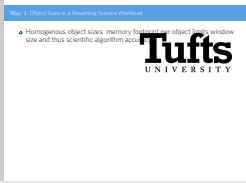
## Way 1: Object Sizes in a Streaming Science Workload

Tufts UNIVERSITY

- Homogenous object sizes: memory footprint per object limits window size and thus scientific algorithm accuracy.








Now, imagine, /you/, are a data-scientist analyzing streams of data, where each data point is some fixed-width record data type. Often times, the analysis you do over this data approximates some property of the entire data set by performing some calculation over snapshots of the data. <slide>

## Way 1: Object Sizes in a Streaming Science Workload

Tufts UNIVERSITY

- Homogenous object sizes: memory footprint per object limits window size and thus scientific algorithm accuracy.
  - E.g. *k*-means algorithm accuracy correlated with available memory, and inversely correlated with runtime.

*k*-means: `http://www.cs.columbia.edu/~rjaiswal/ajmNIPS09.pdf`





And the tradeoff you need to make is to maximize the window size so as to improve algorithmic accuracy, without incurring so much runtime that data streams in faster than you can process it. <slide>

## Way 1: Object Sizes in a Streaming Science Workload

Tufts UNIVERSITY

- Homogenous object sizes: memory footprint per object limits window size and thus scientific algorithm accuracy.
  - E.g. *k*-means algorithm accuracy correlated with available memory, and inversely correlated with runtime.
  - Same for approximating entropy of network packets.

*k*-means: `http://www.cs.columbia.edu/~rjaiswal/ajmNIPS09.pdf`

Entropy: `https://users.ece.cmu.edu/~vsekar/papers/fp013-lall.pdf`



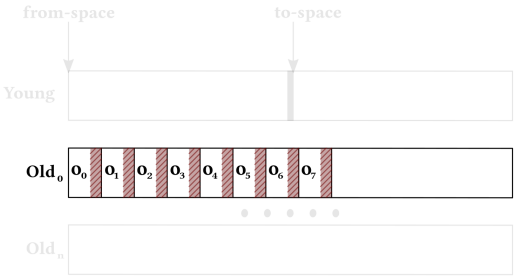


For example, both the k-means algorithm as well as algorithms approximating the entropy of network packets, exhibit accuracy inversely correlated with window size (and thus heap size) /and/ inversely correlated with runtime (because these algorithms are linear in the size of the window) <slide>

## Way 1: Object Sizes in a Streaming Science Workload

Tufts UNIVERSITY

- Homogenous object sizes: memory footprint per object limits window size and thus scientific algorithm accuracy.
  - E.g. *k*-means algorithm accuracy correlated with available memory, and inversely correlated with runtime.
  - Same for approximating entropy of network packets.

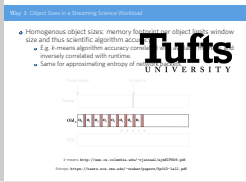



*k*-means: `http://www.cs.columbia.edu/~rjaiswal/ajmNIPS09.pdf`

Entropy: `https://users.ece.cmu.edu/~vsekar/papers/fp013-lall.pdf`







This tradeoff constrains us even further when the data representation chosen for us either wastes space (as indicated by these filled-in regions of each object) /and-or/ the default GC policy incurs a per-object overhead in order to scan and evacuate objects that were destined to survive multiple GCs regardless. <slide> < 7 minutes>

## Way 1: Object Sizes in a Streaming Science Workload

Tufts UNIVERSITY

```
1   type Mac = [u8; 6];
2   type Data = [u8; 13];
3   pub struct Msg { ptr: Addr, }
4   impl Msg {
5     const SIZE : usize = Self::ID_SIZE + Self::POWER_SIZE
6       + Self::MAC_SIZE + Self::EPOCH_SIZE + Self::DATA_SIZE;
7     const ID_OFFSET : usize = 0;
8     const ID_SIZE : usize = size_of::<u32>();
9     const EPOCH_OFFSET : usize = Self::ID_OFFSET + Self::ID_SIZE;
10    const EPOCH_SIZE : usize = size_of::<u64>();
11    const MAC_OFFSET : usize = Self::EPOCH_OFFSET + Self::EPOCH_SIZE;
12    const MAC_SIZE : usize = size_of::<Mac>();
13    const POWER_OFFSET : usize = Self::MAC_OFFSET + Self::MAC_SIZE;
14    const POWER_SIZE : usize = size_of::<u8>();
15    const DATA_OFFSET : usize = Self::POWER_OFFSET + Self::POWER_SIZE;
16    const DATA_SIZE : usize = size_of::<Data>();
17
18    pub fn get_id(&self) -> u32 { unsafe { *(self.ptr.add(Self::ID_OFFSET) as *mut u32) } }
19    pub fn get_epoch(&self) -> u64 { unsafe { *(self.ptr.add(Self::EPOCH_OFFSET) as *mut u64) } }
20    pub fn get_mac(&self) -> Mac { unsafe { *(self.ptr.add(Self::MAC_OFFSET) as *mut Mac) } }
21    pub fn get_power(&self) -> i8 { unsafe { *(self.ptr.add(Self::POWER_OFFSET) as *mut i8) } }
22    pub fn get_data(&self) -> Data { unsafe { *(self.ptr.add(Self::DATA_OFFSET) as *mut Data) } }
23    pub fn set_id(&self, v: u32) { unsafe { *(self.ptr.add(Self::ID_OFFSET) as *mut u32) = v } }
24    pub fn set_epoch(&self, v: u64) { unsafe { *(self.ptr.add(Self::EPOCH_OFFSET) as *mut u64) = v } }
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26    pub fn set_power(&self, v: i8) { unsafe { *(self.ptr.add(Self::POWER_OFFSET) as *mut i8) = v } }
27    pub fn set_data(&self, v: Data) { unsafe { *(self.ptr.add(Self::DATA_OFFSET) as *mut Data) = v } }
28  }
```





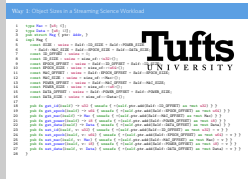


So let's look at a more concrete example. Here, <look at slide> I've implemented a Rust interface for the in-memory representation of a bluetooth packet. <slide>

## Way 1: Object Sizes in a Streaming Science Workload

Tufts UNIVERSITY

```
1  type Mac = [u8; 6];
2  type Data = [u8; 13];
3  pub struct Msg { ptr: Addr, }
4  impl Msg {
5    const SIZE : usize = Self::ID_SIZE + Self::POWER_SIZE
6      + Self::MAC_SIZE + Self::EPOCH_SIZE + Self::DATA_SIZE;
7    const ID_OFFSET : usize = 0;
8    const ID_SIZE : usize = size_of::<u32>();
9    const EPOCH_OFFSET : usize = Self::ID_OFFSET + Self::ID_SIZE;
10   const EPOCH_SIZE : usize = size_of::<u64>();
11   const MAC_OFFSET : usize = Self::EPOCH_OFFSET + Self::EPOCH_SIZE;
12   const MAC_SIZE : usize = size_of::<Mac>();
13   const POWER_OFFSET : usize = Self::MAC_OFFSET + Self::MAC_SIZE;
14   const POWER_SIZE : usize = size_of::<u8>();
15   const DATA_OFFSET : usize = Self::POWER_OFFSET + Self::POWER_SIZE;
16   const DATA_SIZE : usize = size_of::<Data>();
17
18   pub fn get_id(&self) -> u32 { unsafe { *(self.ptr.add(Self::ID_OFFSET) as *mut u32) } }
19   pub fn get_epoch(&self) -> u64 { unsafe { *(self.ptr.add(Self::EPOCH_OFFSET) as *mut u64) } }
20   pub fn get_mac(&self) -> Mac { unsafe { *(self.ptr.add(Self::MAC_OFFSET) as *mut Mac) } }
21   pub fn get_power(&self) -> i8 { unsafe { *(self.ptr.add(Self::POWER_OFFSET) as *mut i8) } }
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27   pub fn set_data(&self, v: Data) { unsafe { *(self.ptr.add(Self::DATA_OFFSET) as *mut Data) = v } }
28 }
```





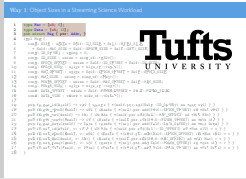

The code looks typical - I define my types up-front, where an “Addr” is synonymous with a word-sized pointer value. <slide>

## Way 1: Object Sizes in a Streaming Science Workload

Tufts UNIVERSITY

```
1   type Mac = [u8; 6];
2   type Data = [u8; 13];
3   pub struct Msg { ptr: Addr, }
4   impl Msg {
5     const SIZE : usize = Self::ID_SIZE + Self::POWER_SIZE
6       + Self::MAC_SIZE + Self::EPOCH_SIZE + Self::DATA_SIZE;
7     const ID_OFFSET : usize = 0;
8     const ID_SIZE : usize = size_of::<u32>();
9     const EPOCH_OFFSET : usize = Self::ID_OFFSET + Self::ID_SIZE;
10    const EPOCH_SIZE : usize = size_of::<u64>();
11    const MAC_OFFSET : usize = Self::EPOCH_OFFSET + Self::EPOCH_SIZE;
12    const MAC_SIZE : usize = size_of::<Mac>();
13    const POWER_OFFSET : usize = Self::MAC_OFFSET + Self::MAC_SIZE;
14    const POWER_SIZE : usize = size_of::<u8>();
15    const DATA_OFFSET : usize = Self::POWER_OFFSET + Self::POWER_SIZE;
16    const DATA_SIZE : usize = size_of::<Data>();
17
18    pub fn get_id(&self) -> u32 { unsafe { *(self.ptr.add(Self::ID_OFFSET) as *mut u32) } }
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27    pub fn set_data(&self, v: Data) { unsafe { *(self.ptr.add(Self::DATA_OFFSET) as *mut Data) = v } }
28  }
```





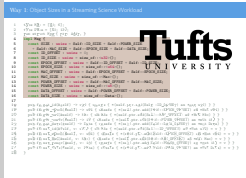

Aaand, I've computed the offset to each field in our bluetooth packet in terms of one another. <slide>

## Way 1: Object Sizes in a Streaming Science Workload

Tufts UNIVERSITY

```
1   type Mac = [u8; 6];
2   type Data = [u8; 13];
3   pub struct Msg { ptr: Addr, }
4   impl Msg {
5     const SIZE : usize = Self::ID_SIZE + Self::POWER_SIZE
6       + Self::MAC_SIZE + Self::EPOCH_SIZE + Self::DATA_SIZE;
7     const ID_OFFSET : usize = 0;
8     const ID_SIZE : usize = size_of::<u32>();
9     const EPOCH_OFFSET : usize = Self::ID_OFFSET + Self::ID_SIZE;
10    const EPOCH_SIZE : usize = size_of::<u64>();
11    const MAC_OFFSET : usize = Self::EPOCH_OFFSET + Self::EPOCH_SIZE;
12    const MAC_SIZE : usize = size_of::<Mac>();
13    const POWER_OFFSET : usize = Self::MAC_OFFSET + Self::MAC_SIZE;
14    const POWER_SIZE : usize = size_of::<u8>();
15    const DATA_OFFSET : usize = Self::POWER_OFFSET + Self::POWER_SIZE;
16    const DATA_SIZE : usize = size_of::<Data>
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18    pub fn get_id(&self) -> u32 { unsafe { *(self.ptr.add(Self::ID_OFFSET) as *mut u32) } }
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27    pub fn set_data(&self, v: Data) { unsafe { *(self.ptr.add(Self::DATA_OFFSET) as *mut Data) = v } }
28  }
```





And with those values I can define getters and setters for accessing those fields. <slide>

## Way 1: Object Sizes in JVM Runtime Code

Tufts UNIVERSITY

```
94   int SCALAR_HEADER_SIZE = JAVA_HEADER_BYTES + OTHER_HEADER_BYTES;
95   int ARRAY_HEADER_SIZE = SCALAR_HEADER_SIZE + ARRAY_LENGTH_BYTES;
96   /** offset of object reference from the lowest memory word */
97   Offset TIB_OFFSET = JAVA_HEADER_OFFSET;
98   Offset STATUS_OFFSET = TIB_OFFSET.plus(STATUS_BYTES);
99   Offset AVAILABLE_BITS_OFFSET =
100    VM.LittleEndian ?
101        STATUS_OFFSET
102      : STATUS_OFFSET.plus(STATUS_BYTES - 1);
103  int HASH_CODE_SHIFT = 2;
104  Word HASH_CODE_MASK =
105    Word.one()
106      .lsh(10)
107      .minus(Word.one())
108      .lsh(HASH_CODE_SHIFT);
109  /** How many bits are allocated to a thin lock? */
110  int NUM_THIN_LOCK_BITS = ADDRESS_BASED_HASHING ? 22 : 20;
111  /** How many bits to shift to get the thin lock? */
112  int THIN_LOCK_SHIFT = ADDRESS_BASED_HASHING ? 10 : 12;
```





This kind of interface already exists out in the wild, exactly when precise control over the layout of memory is needed, as is the case in this snippet of memory manager code defining the offsets to the location of object header words in the JVM. <slide>

## Way 1: JikesRVM Layout Bug Fix

Tufts UNIVERSITY

JikesRVM / **JikesRVM**

### Fix incorrect offset calculation for status bytes.

New issue

**Merged** **erik-brangs** merged 1 commit into `JikesRVM:master` from `cronburg:tib` on May 14, 2018

Conversation 3 · Commits 1 · Checks 0 · Files changed 1 · +2 −1

Changes from all commits · File filter... · Jump to...

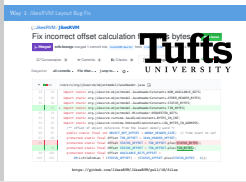
rvm/src/org/jikesrvm/objectmodel/JavaHeader.java

```
29  29    import static org.jikesrvm.objectmodel.JavaHeaderConstants.NUM_AVAILABLE_BITS;
30  30    import static org.jikesrvm.objectmodel.JavaHeaderConstants.OTHER_HEADER_BYTES;
31  31    import static org.jikesrvm.objectmodel.JavaHeaderConstants.STATUS_BYTES;
    32  +  import static org.jikesrvm.objectmodel.JavaHeaderConstants.TIB_BYTES;
32  33    import static org.jikesrvm.objectmodel.MiscHeader.REQUESTED_BITS;
33  34    import static org.jikesrvm.runtime.JavaSizeConstants.BYTES_IN_INT;
34  35    import static org.jikesrvm.runtime.UnboxedSizeConstants.LOG_BYTES_IN_ADDRESS;
95  96      /** offset of object reference from the lowest memory word */
96  97      public static final int OBJECT_REF_OFFSET = ARRAY_HEADER_SIZE;  // from start to ref
97  98      protected static final Offset TIB_OFFSET = JAVA_HEADER_OFFSET;
98          protected static final Offset STATUS_OFFSET = TIB_OFFSET.plus(STATUS_BYTES);
    99      protected static final Offset STATUS_OFFSET = TIB_OFFSET.plus(TIB_BYTES);
99  100     protected static final Offset AVAILABLE_BITS_OFFSET =
100 101         VM.LittleEndian ? (STATUS_OFFSET) : (STATUS_OFFSET.plus(STATUS_BYTES - 1));
```

https://github.com/JikesRVM/JikesRVM/pull/18/files







Buuut, this code is buggy and error-prone. And in fact the code on the previous slide had a latent memory layout bug which went undiscovered for over a decade due to a variable mixup. <slide>

## Way 1: "Eat Your Spinach"

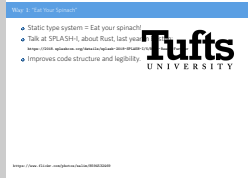
Tufts UNIVERSITY

- Static type system = Eat your spinach!
- Talk at SPLASH-I, about Rust, last year in Boston:

  `https://2018.splashcon.org/details/splash-2018-SPLASH-I/5/Rust-Reach-Further`
- Improves code structure and legibility.





So, even though it takes time to manage these sorts of data interfaces, when done correctly, their presence arguably improves code structure and legibility. Which, also, happens to be why we chose Rust as our target language: to leverage its type system, which /I/ was introduced to last year at a SPLASH-I talk. <slide>

## Way 1: Mechanical Data Formats

Tufts UNIVERSITY

```
1   type Mac = [u8; 6];
2   type Data = [u8; 13];
3   pub struct Msg { ptr: Addr, }
4   impl Msg {
5     const SIZE : usize = Self::ID_SIZE + Self::POWER_SIZE
6       + Self::MAC_SIZE + Self::EPOCH_SIZE + Self::DATA_SIZE;
7     const ID_OFFSET : usize = 0;
8     const ID_SIZE : usize = size_of::<u32>();
9     const EPOCH_OFFSET : usize = Self::ID_OFFSET + Self::ID_SIZE;
10    const EPOCH_SIZE : usize = size_of::<u64>();
11    const MAC_OFFSET : usize = Self::EPOCH_OFFSET + Self::EPOCH_SIZE;
12    const MAC_SIZE : usize = size_of::<Mac>();
13    const POWER_OFFSET : usize = Self::MAC_OFFSET + Self::MAC_SIZE;
14    const POWER_SIZE : usize = size_of::<u8>();
15    const DATA_OFFSET : usize = Self::POWER_OFFSET + Self::POWER_SIZE;
16    const DATA_SIZE : usize = size_of::<Data>();
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18    pub fn get_id(&self) -> u32 { unsafe { *(self.ptr.add(Self::ID_OFFSET) as *mut u32) } }
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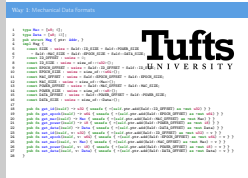


But come on, I'm lazy sometimes, this code is clearly mechanical and has all the hallmarks of boilerplate. Why can't I just generate it, from, say, this:

<slide>

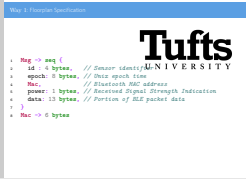
## Way 1: Floorplan Specification

Tufts UNIVERSITY

```
1  Msg -> seq {
2    id : 4 bytes,    // Sensor identifier
3    epoch: 8 bytes, // Unix epoch time
4    Mac,            // Bluetooth MAC address
5    power: 1 bytes, // Received Signal Strength Indication
6    data: 13 bytes, // Portion of BLE packet data
7  }
8  Mac -> 6 bytes
```








And that's exactly what the language-support we've developed, Floorplan, does: it compiles a declarative specification of a memory layout into all the type-safe goodies we want to use but needn't write by hand. ... But if all we got was a pile of fixed-offset getters and setters, then we might as well stick with a struct, because this code here is very similar to a struct, which is the most basic thing you can write in Floorplan. <slide> <10 minutes>

## Way 2: Object Lifetimes in a Streaming Science Workload

Tufts UNIVERSITY

- Temporal-based sliding window of data: non-generational workload.
  - Window Slide Policy[1] traditionally defined by *n* most recent data entries.

[1] Window sliding policy: `https://ieeexplore.ieee.org/document/8456588`

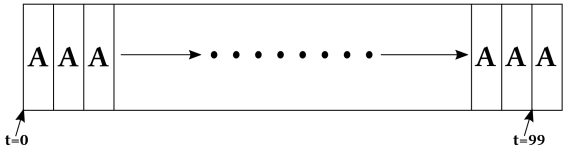





So let's go to our next example. In our domain of window-based streaming applications from before, data typically "comes into view" by way of a window sliding policy, where a traditional policy retains a fixed number *n* of the most recent data entries observed. <slide>

## Way 2: Object Lifetimes in a Streaming Science Workload

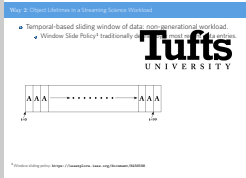
- Temporal-based sliding window of data: non-generational workload.
  - Window Slide Policy[1] traditionally defined by *n* most recent data entries.




[1] Window sliding policy: `https://ieeexplore.ieee.org/document/8456588`







Which might look like this, where we have 100 entries marked as "Allocated".
<slide>

## Way 2: Object Lifetimes in a Streaming Science Workload

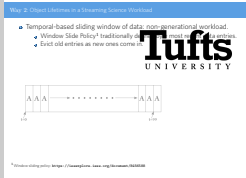
Tufts UNIVERSITY

- Temporal-based sliding window of data: non-generational workload.
  - Window Slide Policy[1] traditionally defined by *n* most recent data entries.
  - Evict old entries as new ones come in.


[1] Window sliding policy: `https://ieeexplore.ieee.org/document/8456588`





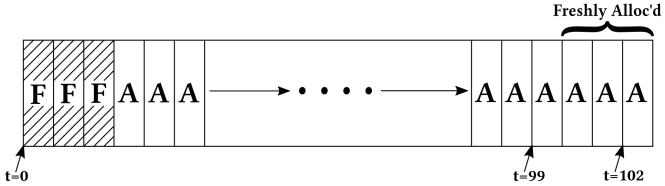


And what we need to do to manage memory is evict old entries as new ones come in. <slide>

## Way 2: Object Lifetimes in a Streaming Science Workload

Tufts UNIVERSITY

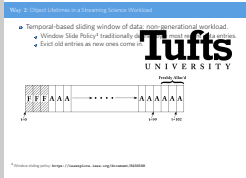
- Temporal-based sliding window of data: non-generational workload.
  - Window Slide Policy[1] traditionally defined by *n* most recent data entries.
  - Evict old entries as new ones come in.




[1] Window sliding policy: `https://ieeexplore.ieee.org/document/8456588`





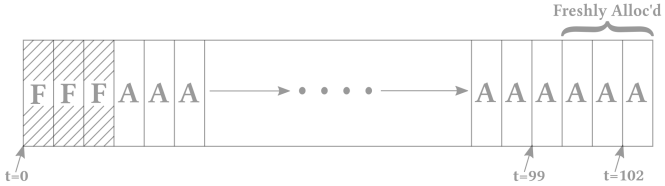


like so, where we've inserted 3 allocated entries at the end of the window, and have now marked the oldest three entries as "F" for Free. <slide>

## Way 2: Object Lifetimes in a Streaming Science Workload

Tufts UNIVERSITY

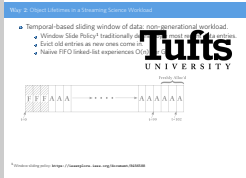
- Temporal-based sliding window of data: non-generational workload.
  - Window Slide Policy[1] traditionally defined by *n* most recent data entries.
  - Evict old entries as new ones come in.
  - Naiive FIFO linked-list experiences O(n) per GC




[1] Window sliding policy: `https://ieeexplore.ieee.org/document/8456588`







Buuut, implementing this naively incurs excessive GC overhead <slide>

## Way 2: Object Lifetimes in a Streaming Science Workload

- Temporal-based sliding window of data: non-generational workload.
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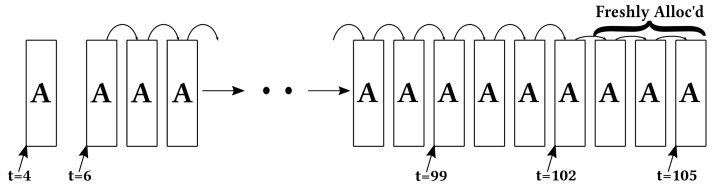
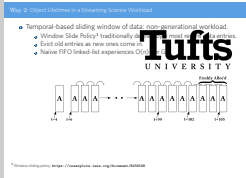
  - Evict old entries as new ones come in.
  - Naiive FIFO linked-list experiences O(n) per GC




[1] Window sliding policy: `https://ieeexplore.ieee.org/document/8456588`



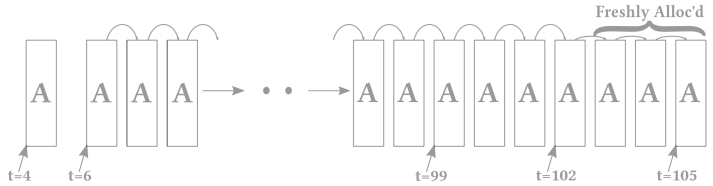




because the GC has to scan the entire linked list to know which objects are still live. <slide>

## Way 2: Object Lifetimes in a Streaming Science Workload

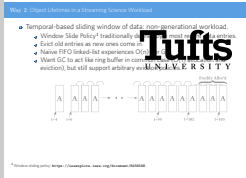
- Temporal-based sliding window of data: non-generational workload.
  - Window Slide Policy[1] traditionally defined by *n* most recent data entries.
  - Evict old entries as new ones come in.
  - Naiive FIFO linked-list experiences O(n) per GC
  - Want GC to act like ring buffer in common case (O(1) allocation and eviction), but still support arbitrary eviction policies.




[1] Window sliding policy: `https://ieeexplore.ieee.org/document/8456588`





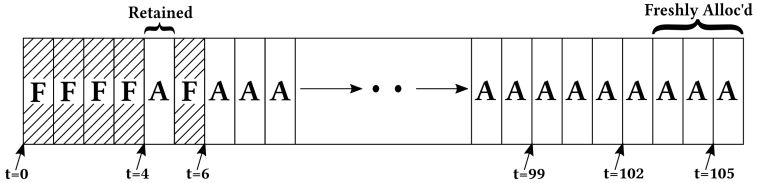


What we /really/ want is for the GC to treat this data structure like a ring buffer in the common case (with constant time allocation and eviction), but to also support an arbitrary eviction policy, where in this example the object at time t equals 4 is retained <slide>

## Way 2: Object Lifetimes in a Streaming Science Workload

Tufts UNIVERSITY

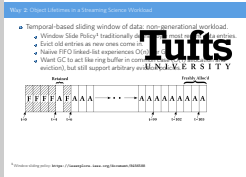
- Temporal-based sliding window of data: non-generational workload.
  - Window Slide Policy[1] traditionally defined by *n* most recent data entries.
  - Evict old entries as new ones come in.
  - Naiive FIFO linked-list experiences O(n) per GC
  - Want GC to act like ring buffer in common case (O(1) allocation and eviction), but still support arbitrary eviction policies.




[1] Window sliding policy: `https://ieeexplore.ieee.org/document/8456588`







but not part of the queue. ... So we do just that: we implement a zero-copying customized allocator which avoids the book-keeping and copying often associated with generational memory managers. <slide>

## Way 2: Object Lifetimes in a Block Allocator

Tufts UNIVERSITY

```
type Addr = *mut u8;
pub fn init(src: &String, heap_sz_mb: usize) -> Result<Ctrl, Error> {
  let file = OpenOptions::new().read(true).write(true).open(src)?;
  let mut mmap_f = unsafe { MmapMut::map_mut(&file)? };
  let fp = mmap_f.as_mut_ptr();

  let heap_sz = heap_sz_mb * BYTES_IN_MB;
  assert!(heap_sz > Block::SIZE, "{}MB not enough for 1 block.", heap_sz_mb);

  let mut mmap_heap = MmapMut::map_anon(heap_sz + Block::SIZE)?;
  let hp : Addr = (((mmap_heap.as_mut_ptr() as usize) >> Block::LOG_SIZE) + 1) << Block::LOG_SIZE;
  let mx = unsafe { hp.add(heap_sz) };

  let mut bs = vec![];
  let first = Block::new(hp);
  let mut curr = first;
  loop {
    let base = unsafe { curr.base.add(Block::SIZE) };
    if unsafe { base.add(Block::SIZE) } > mx { break; }
    curr = Block::new(unsafe { curr.base.add(Block::SIZE) });
    bs.push(curr);
  }

  Ok(Ctrl {
    curr: first,
    next_msg: 0x0 as Addr,
    free_bs: bs,
    used_bs: vec![],
    _fp: mmap_f, fp: fp,
    fp_limit: unsafe { fp.add(file.metadata().unwrap().len() as usize) },
    _hp: mmap_heap, hp: hp, allocd: 0 })
}
```





aand, on this slide, I've implemented the initialization of such a desired memory layout. <slide> <+12min 30sec>

## Way 2: Object Lifetimes in a Block Allocator

Tufts UNIVERSITY

```
type Addr = *mut u8;
pub fn init(src: &String, heap_sz_mb: usize) -> Result<Ctrl, Error> {
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  assert!(heap_sz > Block::SIZE, "{}MB not enough for 1 block.", heap_sz_mb);

  let mut mmap_heap = MmapMut::map_anon(heap_sz + Block::SIZE)?;
  let hp : Addr = (((mmap_heap.as_mut_ptr() as usize) >> Block::LOG_SIZE) + 1) << Block::LOG_SIZE;
  let mx = unsafe { hp.add(heap_sz) };

  let mut bs = vec![];
  let first = Block::new(hp);
  let mut curr = first;
  loop {
    let base = unsafe { curr.base.add(Block::SIZE) };
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    curr = Block::new(unsafe { curr.base.add(Block::SIZE) });
    bs.push(curr);
  }

  Ok(Ctrl {
    curr: first,
    next_msg: 0x0 as Addr,
    free_bs: bs,
    used_bs: vec![],
    _fp: mmap_f, fp: fp,
    fp_limit: unsafe { fp.add(file.metadata().unwrap().len() as usize) },
    _hp: mmap_heap, hp: hp, allocd: 0 })
}
```





First, we initialize access to some out-of-core source of data, such as from the filesystem, as well as compute the desired size of the heap. <slide>

## Way 2: Object Lifetimes in a Block Allocator

Tufts UNIVERSITY

```
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pub fn init(src: &String, heap_sz_mb: usize) -> Result<Ctrl, Error> {
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  let fp = mmap_f.as_mut_ptr();

  let heap_sz = heap_sz_mb * BYTES_IN_MB;
  assert!(heap_sz > Block::SIZE, "{}MB not enough for 1 block.", heap_sz_mb);

  let mut mmap_heap = MmapMut::map_anon(heap_sz + Block::SIZE)?;
  let hp : Addr = (((mmap_heap.as_mut_ptr() as usize) >> Block::LOG_SIZE) + 1) << Block::LOG_SIZE;
  let mx = unsafe { hp.add(heap_sz) };

  let mut bs = vec![];
  let first = Block::new(hp);
  let mut curr = first;
  loop {
    let base = unsafe { curr.base.add(Block::SIZE) };
    if unsafe { base.add(Block::SIZE) } > mx { break; }
    curr = Block::new(unsafe { curr.base.add(Block::SIZE) });
    bs.push(curr);
  }

  Ok(Ctrl {
    curr: first,
    next_msg: 0x0 as Addr,
    free_bs: bs,
    used_bs: vec![],
    _fp: mmap_f, fp: fp,
    fp_limit: unsafe { fp.add(file.metadata().unwrap().len() as usize) },
    _hp: mmap_heap, hp: hp, allocd: 0 })
}
```





Then, we can anonymously m-map a region of virtual address space with which to allocate objects, ..., with the proper alignment so as to support certain bitwise operations later on. <slide>

## Way 2: Object Lifetimes in a Block Allocator

Tufts UNIVERSITY

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pub fn init(src: &String, heap_sz_mb: usize) -> Result<Ctrl, Error> {
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  let mx = unsafe { hp.add(heap_sz) };

  let mut bs = vec![];
  let first = Block::new(hp);
  let mut curr = first;
  loop {
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    if unsafe { base.add(Block::SIZE) } > mx { break; }
    curr = Block::new(unsafe { curr.base.add(Block::SIZE) });
    bs.push(curr);
  }

  Ok(Ctrl {
    curr: first,
    next_msg: 0x0 as Addr,
    free_bs: bs,
    used_bs: vec![],
    _fp: mmap_f, fp: fp,
    fp_limit: unsafe { fp.add(file.metadata().unwrap().len() as usize) },
    _hp: mmap_heap, hp: hp, allocd: 0 })
}
```





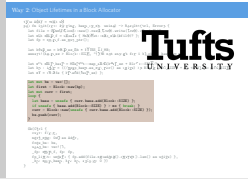

Next, we iterate through the entire heap's address space, carving up memory into blocks. <slide>

## Way 2: Object Lifetimes in a Block Allocator

Tufts UNIVERSITY

```
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pub fn init(src: &String, heap_sz_mb: usize) -> Result<Ctrl, Error> {
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  let heap_sz = heap_sz_mb * BYTES_IN_MB;
  assert!(heap_sz > Block::SIZE, "{}MB not enough for 1 block.", heap_sz_mb);

  let mut mmap_heap = MmapMut::map_anon(heap_sz + Block::SIZE)?;
  let hp : Addr = (((mmap_heap.as_mut_ptr() as usize) >> Block::LOG_SIZE) + 1) << Block::LOG_SIZE;
  let mx = unsafe { hp.add(heap_sz) };

  let mut bs = vec![];
  let first = Block::new(hp);
  let mut curr = first;
  loop {
    let base = unsafe { curr.base.add(Block::SIZE) };
    if unsafe { base.add(Block::SIZE) } > mx { break; }
    curr = Block::new(unsafe { curr.base.add(Block::SIZE) });
    bs.push(curr);
  }

  Ok(Ctrl {
    curr: first,
    next_msg: 0x0 as Addr,
    free_bs: bs,
    used_bs: vec![],
    _fp: mmap_f, fp: fp,
    fp_limit: unsafe { fp.add(file.metadata().unwrap().len() as usize) },
    _hp: mmap_heap, hp: hp, allocd: 0 })
}
```





And finally, we construct a controller data structure tracking memory-management-related bookkeeping. <slide>

## Way 2: Object Lifetimes in a Block Allocator

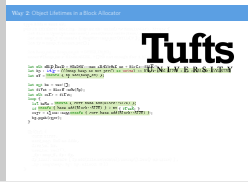
Tufts UNIVERSITY

```
let mut mmap_heap = MmapMut::map_anon(heap_sz + Block::SIZE)?;
let hp : Addr = (((mmap_heap.as_mut_ptr() as usize) >> Block::LOG_SIZE) + 1) << Block::LOG_SIZE;
let mx = unsafe { hp.add(heap_sz) };

let mut bs = vec![];
let first = Block::new(hp);
let mut curr = first;
loop {
  let base = unsafe { curr.base.add(Block::SIZE) };
  if unsafe { base.add(Block::SIZE) } > mx { break; }
  curr = Block::new(unsafe { curr.base.add(Block::SIZE) });
  bs.push(curr);
}
```







Now, I'd like to focus your attention on /theeese/, highlighted, memory layout operations.<slide>

## Way 2: Object Lifetimes in a Block Allocator

Tufts UNIVERSITY

Specification:

```
Heap -> # Block
Block @|2^21 bytes|@ -> # Msg
```

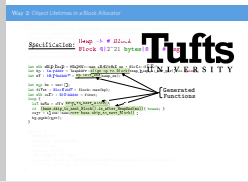
```
let mut mmap_heap = MmapMut::map_anon(heap_sz + Block::SIZE)?;
let hp : HeapAddr = HeapAddr::align_up_to_Block(mmap_heap.as_mut_ptr() as usize);
let mx : HeapEndAddr = hp.init_end(heap_sz);

let mut bs = vec![];
let first : BlockAddr = Block::new(hp);
let mut curr : BlockAddr = first;
loop {
  let base = curr.skip_to_next_Block();
  if (base.skip_to_next_Block().is_after_HeapEnd(mx)) { break; }
  curr = Block::new(curr.base.skip_to_next_Block());
  bs.push(curr);
}
```

Generated Functions







Well, instead we can write a declarative layout specification, in Floorplan, and get out an interface supporting statically-typed versions of the exact same operations.

## Way 2: Object Lifetimes in a Block Allocator

Tufts UNIVERSITY

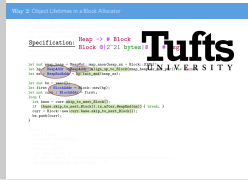
**Specification:** `Heap -> # Block`
`Block @|2^21 bytes|@ -> # Msg`

```
let mut mmap_heap = MmapMut::map_anon(heap_sz + Block::SIZE)?;
let hp : HeapAddr = HeapAddr::align_up_to_Block(mmap_heap.as_mut_ptr() as usize);
let mx : HeapEndAddr = hp.init_end(heap_sz);

let mut bs = vec![];
let first : BlockAddr = Block::new(hp);
let mut curr : BlockAddr = first;
loop {
  let base = curr.skip_to_next_Block();
  if  (base.skip_to_next_Block().is_after_HeapEnd(mx)) { break; }
  curr = Block::new(curr.base.skip_to_next_Block());
  bs.push(curr);
}
```







Those operations, get associated with generated address types, one for each Floorplan declaration, such as “BlockAddr”, on the slide, but also “HeapEndAddr”, which points to the first word of memory past the end of a “Heap”.

## Way 2: Object Lifetimes in a Block Allocator

Tufts UNIVERSITY

Specification:

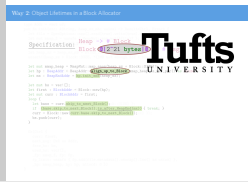
```
Heap -> # Block
Block @|2^21 bytes|@ -> # Msg
```

```
let mut mmap_heap = MmapMut::map_anon(heap_sz + Block::SIZE)?;
let hp : HeapAddr = HeapAddr::align_up_to_Block(mmap_heap.as_mut_ptr() as usize);
let mx : HeapEndAddr = hp.init_end(heap_sz);

let mut bs = vec![];
let first : BlockAddr = Block::new(hp);
let mut curr : BlockAddr = first;
loop {
  let base = curr.skip_to_next_Block();
  if (base.skip_to_next_Block().is_after_HeapEnd(mx)) { break; }
  curr = Block::new(curr.base.skip_to_next_Block());
  bs.push(curr);
}
```







The first operation, “align_up_to_block”, gets generated as a member function of the HeapAddr type because (1) the first thing in a Heap is a block, and (2) that first block has a 2-to-the-21 byte alignment (and size) as indicated by this what I like to call “at-mag” operator, in the spec.

## Way 2: Object Lifetimes in a Block Allocator

Tufts UNIVERSITY

Specification: Heap -> # Block

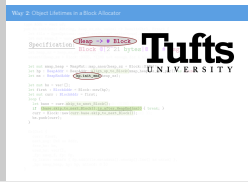
Block @|2^21 bytes|@ -> # Msg

```
let mut mmap_heap = MmapMut::map_anon(heap_sz + Block::SIZE)?;
let hp : HeapAddr = HeapAddr::align_up_to_Block(mmap_heap.as_mut_ptr() as usize);
let mx : HeapEndAddr = hp.init_end(heap_sz);

let mut bs = vec![];
let first : BlockAddr = Block::new(hp);
let mut curr : BlockAddr = first;
loop {
  let base = curr.skip_to_next_Block();
  if (base.skip_to_next_Block().is_after_HeapEnd(mx)) { break; }
  curr = Block::new(curr.base.skip_to_next_Block());
  bs.push(curr);
}
```







The second operation, “init_end”, gets generated because a heap is defined to be any number (zero or more) blocks. This is what the “pound” operator does: it acts exactly like a prefix-notation Kleene-star regular expression. In contrast, the “pound” inside of our “Block”, declaration, is bounded to 2-to-the-21 bytes, and so /its/ “init_end” function does /not/ take in an unsigned integer parameter.

## Way 2: Object Lifetimes in a Block Allocator

Tufts UNIVERSITY

Specification: Heap -> # Block
Block @|2^21 bytes|@ -> # Msg

```
let mut mmap_heap = MmapMut::map_anon(heap_sz + Block::SIZE)?;
let hp : HeapAddr = HeapAddr::align_up_to_Block(mmap_heap.as_mut_ptr() as usize);
let mx : HeapEndAddr = hp.init_end(heap_sz);

let mut bs = vec![];
let first : BlockAddr = Block::new(hp);
let mut curr : BlockAddr = first;
loop {
  let base = curr.skip_to_next_Block();
  if  (base.skip_to_next_Block().is_after_HeapEnd(mx)) { break; }
  curr = Block::new(curr.base.skip_to_next_Block());
  bs.push(curr);
}
```





This next operation, “skip_to_next_Block”, gets associated with the “Block-Addr” type because Blocks in a Heap are iterable.

## Way 2: Object Lifetimes in a Block Allocator

Tufts UNIVERSITY

Specification: Heap -> # Block

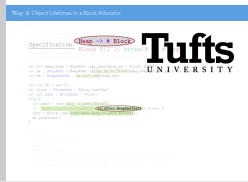
Block @|2^21 bytes|@ -> # Msg

```
let mut mmap_heap = MmapMut::map_anon(heap_sz + Block::SIZE)?;
let hp : HeapAddr = HeapAddr::align_up_to_Block(mmap_heap.as_mut_ptr() as usize);
let mx : HeapEndAddr = hp.init_end(heap_sz);

let mut bs = vec![];
let first : BlockAddr = Block::new(hp);
let mut curr : BlockAddr = first;
loop {
  let base = curr.skip_to_next_Block();
  if is_after_HeapEnd(mx) { break; }
  curr = Block::new(curr.base.skip_to_next_Block());
  bs.push(curr);
}
```







And lastly, an “is_after” comparison function, producing the boolean you would expect, gets generated for the BlockAddr type /relative/ to a HeapEndAddr (the only parameter) because a Heap contains, and ends with, iterable blocks. If we had, instead, put some metadata at the end of a Heap, then a function with a /different/ type signature, gets generated.

## Way 2: Object Lifetimes in a Block Allocator

Tufts UNIVERSITY

```
type Addr = *mut u8;
pub fn init(src: &String, heap_sz_mb: usize) -> Result<Ctrl, Error> {
  let file = OpenOptions::new().read(true).write(true).open(src)?;
  let mut mmap_f = unsafe { MmapMut::map_mut(&file)? };
  let fp = mmap_f.as_mut_ptr();

  let heap_sz = heap_sz_mb * BYTES_IN_MB;
  assert!(heap_sz > Block::SIZE, "{}MB not enough for 1 block.", heap_sz_mb);

  let mut mmap_heap = MmapMut::map_anon(heap_sz + Block::SIZE)?;
  let hp : Addr = (((mmap_heap.as_mut_ptr() as usize) >> Block::LOG_SIZE) + 1) << Block::LOG_SIZE;
  let mx = unsafe { hp.add(heap_sz) };

  let mut bs = vec![];
  let first = Block::new(hp);
  let mut curr = first;
  loop {
    let base = unsafe { curr.base.add(Block::SIZE) };
    if unsafe { base.add(Block::SIZE) } > mx { break; }
    curr = Block::new(unsafe { curr.base.add(Block::SIZE) });
    bs.push(curr);
  }

  Ok(Ctrl {
    curr: first,
    next_msg: 0x0 as Addr,
    free_bs: bs,
    used_bs: vec![],
    _fp: mmap_f, fp: fp,
    fp_limit: unsafe { fp.add(file.metadata().unwrap().len() as usize) },
    _hp: mmap_heap, hp: hp, allocd: 0 })
}
```





So hold on, I wrote this code myself, and you may be thinking to yourself: why am I writing this low-level code when there exist frameworks <slide>

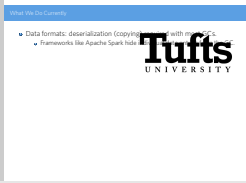
## What We Do Currently

Tufts UNIVERSITY

- Data formats: deserialization (copying) required with most GCs.
  - Frameworks like Apache Spark hide individual data entries from the GC.








like Apache Spark, which will do this for me. Spark achieves good performance by /hiding/ data entries from the garbage collector. <slide>

## What We Do Currently: Allocation in Apache Spark

Tufts UNIVERSITY

```
1   /**A simple {@link MemoryAllocator} that can allocate up to 16GB using a JVM long primitive array. */
2   public class HeapMemoryAllocator implements MemoryAllocator {
3     private final Map<Long, LinkedList<WeakReference<long[]>>> bufferPoolsBySize = new HashMap<>();
4     public MemoryBlock allocate(long size) throws OutOfMemoryError {
5       int numWords = (int) ((size + 7) / 8);
6       long alignedSize = numWords * 8L;
7       assert (alignedSize >= size);
8       if (shouldPool(alignedSize)) {
9         synchronized (this) {
10          final LinkedList<WeakReference<long[]>> pool = bufferPoolsBySize.get(alignedSize);
11          if (pool != null) {
12            while (!pool.isEmpty()) {
13              final WeakReference<long[]> arrayReference = pool.pop();
14              final long[] array = arrayReference.get();
15              if (array != null) {
16                assert (array.length * 8L >= size);
17                MemoryBlock memory = new MemoryBlock(array, Platform.LONG_ARRAY_OFFSET, size);
18                if (MemoryAllocator.MEMORY_DEBUG_FILL_ENABLED) {
19                  memory.fill(MemoryAllocator.MEMORY_DEBUG_FILL_CLEAN_VALUE); }
20                return memory; } }
21            bufferPoolsBySize.remove(alignedSize); } } }
22      long[] array = new long[numWords];
23      MemoryBlock memory = new MemoryBlock(array, Platform.LONG_ARRAY_OFFSET, size);
24      if (MemoryAllocator.MEMORY_DEBUG_FILL_ENABLED) {
25        memory.fill(MemoryAllocator.MEMORY_DEBUG_FILL_CLEAN_VALUE); }
26      return memory; }
```

https://github.com/apache/spark/blob/0b9ccd55c2986957863dcad3b44ce80403eecfa1/common/unsafe/src/main/java/

org/apache/spark/unsafe/memory/HeapMemoryAllocator.java#L48






In this code, taken from Spark's allocator, <slide>

## What We Do Currently: Allocation in Apache Spark

Tufts UNIVERSITY

```
1   /**A simple {@link MemoryAllocator} that can allocate up to 16GB using a JVM long primitive array. */
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```
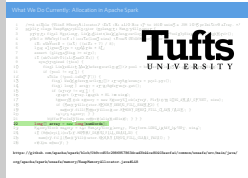

https://github.com/apache/spark/blob/0b9ccd55c2986957863dcad3b44ce80403eecfa1/common/unsafe/src/main/java/org/apache/spark/unsafe/memory/HeapMemoryAllocator.java#L48







Data is allocated into enormous Java-native long arrays, entirely avoiding memory reclamation by the garbage collector. Well, once you've decided to go this route, where, your memory abstraction is just a raw array of bytes, you're back to square one: language support for memory layout must be built from scratch, be it in Java, C and C++, or Rust. The latter of which, Rust, now has Floorplan. <slide>

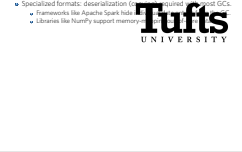
## What We Do Currently

Tufts UNIVERSITY

- Specialized formats: deserialization (copying) required with most GCs.
  - Frameworks like Apache Spark hide individual data entries from the GC.
  - Libraries like NumPy support memory-mapping out-of-core data.







But wait, I forgot a language. What if I want to implement some memory management in Python to optimize data import? (because, after all, I'm interested in scientific analyses) <slide>

## What We Do Currently: NumPy's NPY File Format

Tufts UNIVERSITY

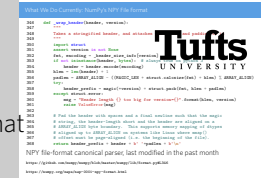
```
346    def _wrap_header(header, version):
347        """
348        Takes a stringified header, and attaches the prefix and padding to it
349        """
350        import struct
351        assert version is not None
352        fmt, encoding = _header_size_info[version]
353        if not isinstance(header, bytes):  # always true on python 3
354            header = header.encode(encoding)
355        hlen = len(header) + 1
356        padlen = ARRAY_ALIGN - ((MAGIC_LEN + struct.calcsize(fmt) + hlen) % ARRAY_ALIGN)
357        try:
358            header_prefix = magic(*version) + struct.pack(fmt, hlen + padlen)
359        except struct.error:
360            msg = "Header length {} too big for version={}".format(hlen, version)
361            raise ValueError(msg)
362
363        # Pad the header with spaces and a final newline such that the magic
364        # string, the header-length short and the header are aligned on a
365        # ARRAY_ALIGN byte boundary.  This supports memory mapping of dtypes
366        # aligned up to ARRAY_ALIGN on systems like Linux where mmap()
367        # offset must be page-aligned (i.e. the beginning of the file).
368        return header_prefix + header + b' '*padlen + b'\n'
```

NPY file-format canonical parser, last modified in the past month

`https://github.com/numpy/numpy/blob/master/numpy/lib/format.py#L346`








And that's exactly what the NumPy developers did: they wrote python code, which, among other things, <slide>

## What We Do Currently: NumPy's NPY File Format

Tufts UNIVERSITY

```
346   def _wrap_header(header, version):
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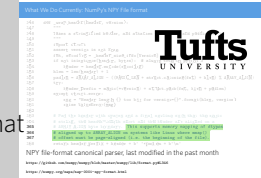


manages data layouts to support proper mmap alignment.

## What We Do Currently: Informal Comments

Tufts UNIVERSITY

```
90  Format Version 1.0
91  ------------------
92  The first 6 bytes are a magic string: exactly ``\\x93NUMPY``.
93  The next 1 byte is an unsigned byte: the major version number of the file
94  format, e.g. ``\\x01``.
95
96  The next 1 byte is an unsigned byte: the minor version number of the file
97  format, e.g. ``\\x00``. Note: the version of the file format is not tied
98  to the version of the numpy package.
99
100 The next 2 bytes form a little-endian unsigned short int: the length of
101 the header data HEADER_LEN.
102
103 The next HEADER_LEN bytes form the header data describing the array's
104 format. It is an ASCII string which contains a Python literal expression
105 of a dictionary. It is terminated by a newline (``\\n``) and padded with
106 spaces (``\\x20``) to make the total of
107 ``len(magic string) + 2 + len(length) + HEADER_LEN`` be evenly divisible
108 by 64 for alignment purposes.
```






But not every file format, or memory layout, is obvious from the code that implements it. Instead, we're left writing notes to our future selves explaining, like described here for the NumPy NPY file format, the design decisions of our layout. With Floorplan, you can write down otherwise unspecified relationships among pieces of a layout, not formalized anywhere else. <slide>

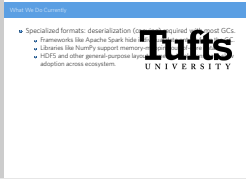
## What We Do Currently

Tufts UNIVERSITY

- Specialized formats: deserialization (copying) required with most GCs.
  - Frameworks like Apache Spark hide individual data entries from the GC.
  - Libraries like NumPy support memory-mapping out-of-core data.
  - HDF5 and other general-purpose layout framework solutions have slow adoption across ecosystem.








And to drive home the point even further, even extensively formalized and well-engineered layout formats, like HDF5, come with their own baggage. <slide>

tensorflow / io

# Support HDF5 in tensorflow-io #174

Open **yongtang** opened this issue on Apr 4 · 20 comments

New issue

**yongtang** commented on Apr 4 — Member

The follow is from tensorflow/tensorflow#27510

> I am currently using HDF5 files (.h5 or .hdf5) to store my data, which is a data type frequently used in scientific research. (See #2089 for a similar but different request which makes the case for a HDF5 interface nicely). It is very convenient and widely used. MATLAB for example uses HDF5 files for large files. Indeed, it is much more convenient to use than Tensorflow's TFRecord format.

> However, in Tensorflow, there is no native support for HDF5 files in the tf.data.Dataset API, which is supposed to be the new API for all data loading. Currently, I am using tf.py_funtion to load my data for the simple reason that tf Dataset is always in graph mode and hence cannot give out the values of the files that I want it to read.

> Moreover, I have found that reading an HDF5 file in this way DRAMATICALLY slows down data I/O for unknown reasons. When I used the tf.keras.utils.Sequence API to read HDF5 files without the supposed optimizations that tensorflow is making, an operation that previously took hours now took just a few seconds. (However, I suspect that using tf.defun somehow got tangled up with this. I am not sure why but when I removed some lines, the code sped up, but was still much slower than even a single threaded for loop)

**Assignees**
No one assigned

**Labels**
feature

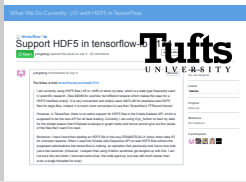
**Projects**
None yet

**Milestone**
No milestone

**5 participants**








HDF5, the widely portable scientific file format, continues to lag to be adopted in versatile ways. For example. When attempting to analyze some bluetooth packets with Tensorflow, before picking up Rust in my previous examples, I came upon this Github issue. Basically, in addition to experiencing slow load times of HDF5 files, the issue pertains to the support of efficient /streaming/ of HDF5 files.

README.md

# TensorFlow I/O

build error | pypi package 0.7.0 | CRAN 0.4.0

TensorFlow I/O is a collection of file systems and file formats that are not available in TensorFlow's built-in support.

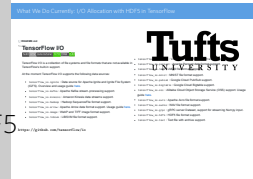
At the moment TensorFlow I/O supports the following data sources:

- `tensorflow_io.ignite` : Data source for Apache Ignite and Ignite File System (IGFS). Overview and usage guide here.
- `tensorflow_io.kafka` : Apache Kafka stream-processing support.
- `tensorflow_io.kinesis` : Amazon Kinesis data streams support.
- `tensorflow_io.hadoop` : Hadoop SequenceFile format support.
- `tensorflow_io.arrow` : Apache Arrow data format support. Usage guide here.
- `tensorflow_io.image` : WebP and TIFF image format support.
- `tensorflow_io.libsvm` : LIBSVM file format support.
- `tensorflow_io.ffmpeg` : Video and Audio file support with FFmpeg.
- `tensorflow_io.parquet` : Apache Parquet data format support.
- `tensorflow_io.lmdb` : LMDB file format support.
- `tensorflow_io.mnist` : MNIST file format support.
- `tensorflow_io.pubsub` : Google Cloud Pub/Sub support.
- `tensorflow_io.bigtable` : Google Cloud Bigtable support.
- `tensorflow_io.oss` : Alibaba Cloud Object Storage Service (OSS) support. Usage guide here.
- `tensorflow_io.avro` : Apache Avro file format support.
- `tensorflow_io.audio` : WAV file format support.
- `tensorflow_io.grpc` : gRPC server Dataset, support for streaming Numpy input.
- `tensorflow_io.hdf5` : HDF5 file format support.
- `tensorflow_io.text` : Text file with archive support.

`https://github.com/tensorflow/io`








Well, it's no wonder I'm still waiting for streaming support when such a popular library needs to cater to so many different domains.<slide>

## What We Do Currently: I/O Allocation with HDF5 in TensorFlow

Tufts UNIVERSITY

README.md

# TensorFlow I/O

build error pypi package 0.7.0 CRAN 0.4.0

TensorFlow I/O is a collection of file systems and file formats that are not available in TensorFlow's built-in support.

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- `tensorflow_io.text` : Text file with archive support.

`https://github.com/tensorflow/io`





It even supports the format I desired, just not in the way I required.<slide>

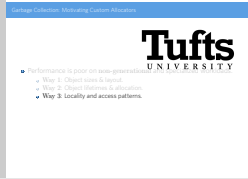
## Garbage Collection: Motivating Custom Allocators

Tufts UNIVERSITY

- Performance is poor on non-generational and specialized workloads.
  - Way 1: Object sizes & layout.
  - Way 2: Object lifetimes & allocation.
  - Way 3: Locality and access patterns.

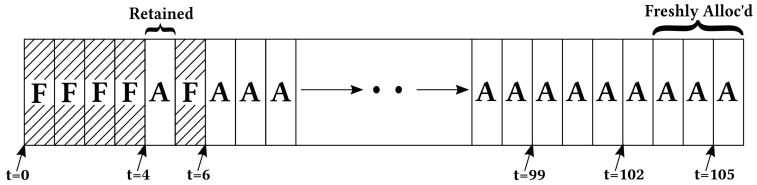






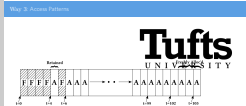

Which brings us to our third and final program characteristic from before: data access patterns. <slide>

## Way 3: Access Patterns







For example, we might want to ensure that the next $100$ data entries span no more than two system pages, even in the presence of retained packets like at $t$ equals $4$. <slide>

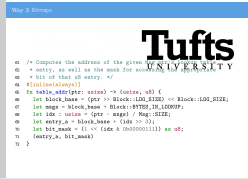
## Way 3: Bitmaps

Tufts UNIVERSITY

```
61  /* Computes the address of the given Msg ptr's lookup table
62   * entry, as well as the mask for accessing the appropriate
63   * bit of that u8 entry. */
64  #[inline(always)]
65  fn table_addr(ptr: usize) -> (usize, u8) {
66    let block_base = (ptr >> Block::LOG_SIZE) << Block::LOG_SIZE;
67    let msgs = block_base + Block::BYTES_IN_LOOKUP;
68    let idx : usize = (ptr - msgs) / Msg::SIZE;
69    let entry_a = block_base + (idx >> 3);
70    let bit_mask = (1 << (idx & 0b00000111)) as u8;
71    (entry_a, bit_mask)
72  }
```

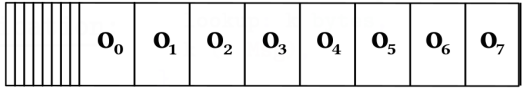






Aaaand, to do that, we first need to write some code which figures out which Msgs in a block are free and which ones are allocated, as done in this hand-written Rust code.

## Way 3: Bitmaps

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63   * bit of that u8 entry. */
64  #[inline(always)]
65  fn table_addr(ptr: usize) -> (usize, u8) {
66    let block_base = (ptr >> Block::LOG_SIZE) << Block::LOG_SIZE;
67    let msgs = block_base + Block::BYTES_IN_LOOKUP;
68    let idx : usize = (ptr - msgs) / Msg::SIZE;
69    let entry_a = block_base + (idx >> 3);
70    let bit_mask = (1 << (idx & 0b00000111)) as u8;
71    (entry_a, bit_mask)
72  }
```
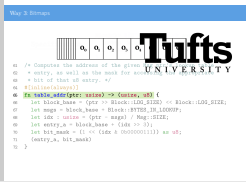
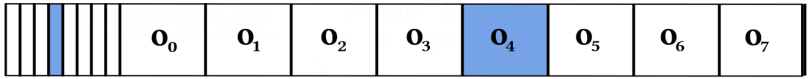




This /code/, computes the address of the *n*-th bit, in a lookup table located at the beginning of a block (these small bit-sized entries), /given/ a pointer to the *n*-th Msg object (o-zero through o-eight here).

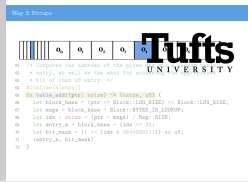
## Way 3: Bitmaps




```rust
/* Computes the address of the given Msg ptr's lookup table
 * entry, as well as the mask for accessing the appropriate
 * bit of that u8 entry. */
#[inline(always)]
fn table_addr(ptr: usize) -> (usize, u8) {
  let block_base = (ptr >> Block::LOG_SIZE) << Block::LOG_SIZE;
  let msgs = block_base + Block::BYTES_IN_LOOKUP;
  let idx : usize = (ptr - msgs) / Msg::SIZE;
  let entry_a = block_base + (idx >> 3);
  let bit_mask = (1 << (idx & 0b00000111)) as u8;
  (entry_a, bit_mask)
}
```

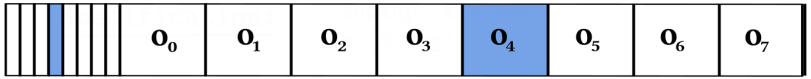






For example, object o-four and the corresponding bit we compute are highlighted here.

## Way 3: Bitmaps

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63   * bit of that u8 entry. */
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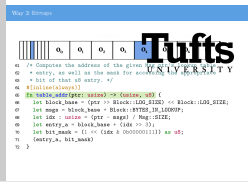
67    let msgs = block_base + Block::BYTES_IN_LOOKUP;
68    let idx : usize = (ptr - msgs) / Msg::SIZE;
69    let entry_a = block_base + (idx >> 3);
70    let bit_mask = (1 << (idx & 0b00000111)) as u8;
71    (entry_a, bit_mask)
72  }
```







The address of that bit is represented as an 8-bit mask, the u8 returned by this function, and that mask /applies/ to the value found at the address represented by the usize returned.

## Way 3: Bitmaps

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```
Specification:   Block<k> @|2^21 bytes|@ -> seq {
                   lookup: k bits, 1 bits,
                   msgs:   k Msg,
                 }
```

```
61  /* Computes the address of the given Msg ptr's lookup table
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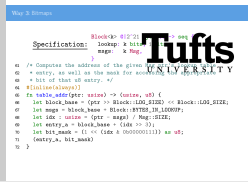

A key insight we had with Floorplan, is that that memory relationship can be described as a non-context-free grammar.

## Way 3: Bitmaps

Specification:

```
Block<k> @|2^21 bytes|@ -> seq {
  lookup: k bits, 1 bits,
  msgs:   k Msg,
}
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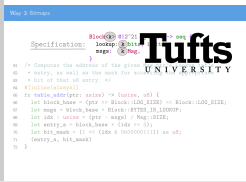

/Which/, is implemented as formal parameters to Floorplan declarations, representing non-negative integer repetitions, like so with the variable *k*.

## Way 3: Bitmaps

Tufts UNIVERSITY

```
Specification:   Block<k> @|2^21 bytes|@ -> seq {
                   lookup: k bits, 1 bits,
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```
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65  fn table_addr(ptr: MsgAddr) -> (BitsAddr, BitsMask) {
66    let block : BlockAddr = ptr.get_containing_BlockAddr();
67    let msgs : ObjsAddr = block.msgs();
68    let idx : usize = msgs.get_idx_of(ptr);
69    let entry_a : BitsAddr = block.lookup().get_BitsAddr_of_idx
70                                                    (idx);
71    let bit_mask : BitsMask = BitsMask::from_idx(idx);
72    (entry_a, bit_mask)
73  }
```






From this spec, the compiler generates all the necessary array-like operations.

## Way 3: Bitmaps

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Specification:

```
Block<k> @|2^21 bytes|@ -> seq {
  lookup: k bits, 1 bits,
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                                                    (idx);
70    let bit_mask : BitsMask = BitsMask::from_idx(idx);
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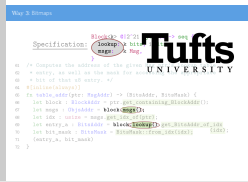
```







As before, this includes basic field accessors.

## Way 3: Bitmaps

Tufts UNIVERSITY

Specification:

```
Block<k> @|2^21 bytes|@ -> seq {
  lookup: k bits, 1 bits,
  msgs:   k Msg,
}
```

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69    let entry_a : BitsAddr = block.lookup().get_BitsAddr_of_idx
70                                                    (idx);
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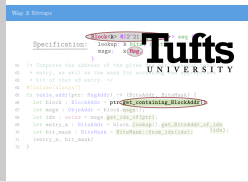
72    (entry_a, bit_mask)
73  }
```







Now, this operation gets generated /because/ messages are inside of blocks, and a block's alignment is greater than or equal to its size

## Way 3: Bitmaps

Tufts UNIVERSITY

Specification:

```
Block<k> @|2^21 bytes|@ -> seq {
  lookup: k bits, 1 bits,
  msgs:   k Msg,
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```

```
61 /* Computes the address of the given Msg ptr's lookup table
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70                                                 (idx);
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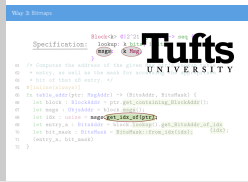
73 }
```







And so on, where we can determine the index of some message into our array,<slide>

## Way 3: Bitmaps

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```
Specification:  Block<k> @|2^21 bytes|@ -> seq {
                  lookup: k bits, 1 bits,
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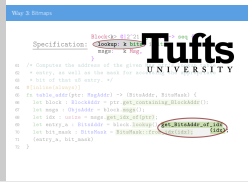
70                                                    (idx);
71    let bit_mask : BitsMask = BitsMask::from_idx(idx);
72    (entry_a, bit_mask)
   }
```







we can discover the n-th thing in our lookup table

## Way 3: Bitmaps

Tufts UNIVERSITY

Specification:

```
Block<k> @|2^21 bytes|@ -> seq {
  lookup: k bits -> 1 bits,
  msgs:   k Msg,
}
```

```
61 /* Computes the address of the given Msg ptr's lookup table
62  * entry, as well as the mask for accessing the appropriate
63  * bit of that u8 entry. */
64 #[inline(always)]
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69   let entry_a : BitsAddr = block.lookup().get_BitsAddr_of_idx
70   let bit_mask : BitsMask = BitsMask::from_idx(idx);
                                                    (idx);
71   (entry_a, bit_mask)
72 }
```






aaand as a bonus we get a bit-mask data type for selecting just the bit we care about.

## Semantics Un-mentioned in this Talk

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- Byte order.
- Macros.
- Architectural constants.
- Performance characteristics.
- Reduction semantics defining a Floorplan type.
- Compiler implementation details.
- Coq proofs verifying certain language-level properties.





Semantics Un-mentioned in this Talk
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- Byte order.
- Macros.
- Architectural constants.
- Performance characteristics.
- Reduction semantics defining a Floorplan type.
- Compiler implementation details.
- Coq proofs verifying certain language-level properties.

/Aaand/ that's Floorplan. Except for all the linguistic and semantic formalisms that I don't have time to tell you about today. And did not prepare slides for.

## What do we Lose?

- New spatially optimized data structures must be written with custom collection in mind => but Floorplan takes care of the types.





What do we Lose?
- New spatially optimized data structures must be written with custom collection in mind => but Floorplan takes care of the types.

Instead, I showed you that a memory layout is only as precise as the code, and type system, that implements it.

- Ignoring of diminishing returns on ever-improving modern commodity hardware.
- Pre-emptively optimizing microbenchmarks deemed representative.
- Incurring bookkeeping burdens for each custom memory manager.
- Need to write custom interfaces to memory debuggers like Valgrind, GDB, and Purify.
- Sunk costs due to how difficult they are to write in the first place!





Common Pitfalls with Custom Allocators and Collectors
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- Ignoring of diminishing returns on ever-improving modern commodity hardware.
- Pre-emptively optimizing microbenchmarks deemed representative.
- Incurring bookkeeping burdens for each custom memory manager.
- Need to write custom interfaces to memory debuggers like Valgrind, GDB, and Purify.
- Sunk costs due to how difficult they are to write in the first place!

Which is why, regardless of all the ways custom managers wind up being misapplied (a number of which are listed here), the difficulty associated with implementing pointer types should not be a valid argument against layout customization.

# Questions?





Questions
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Questions?

Thank you for your time.

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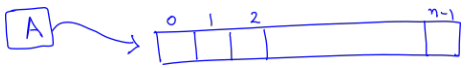
Example: if we need an array of n ints, then we can do

```
int* A = malloc(n*sizeof(int));
```




A holds the address of the first element of this block of 4n bytes, and A can be used as an array. For example,

```
if (A != NULL)
 for (i=0;i<n;i++)
 A[i] = 0;
```

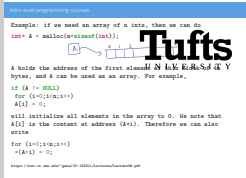
will initialize all elements in the array to 0. We note that A[i] is the content at address (A+i). Therefore we can also write

```
for (i=0;i<n;i++)
 *(A+i) = 0;
```

https://www.cs.cmu.edu/~guna/15-123S11/Lectures/Lecture08.pdf





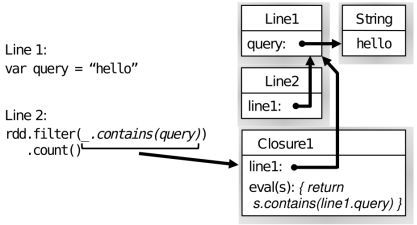


### 5.3 Memory Management

Spark provides three options for storage of persistent RDDs: in-memory storage as deserialized Java objects, in-memory storage as serialized data, and on-disk storage. The first option provides the fastest performance, because the Java VM can access each RDD element natively. The second option lets users choose a more memory-efficient representation than Java object graphs when space is limited, at the cost of lower performance.[8] The third option is useful for RDDs that are too large to keep in RAM but costly to recompute on each use.

To manage the limited memory available, we use an LRU eviction policy at the level of RDDs. When a new RDD partition is computed but there is not enough space to store it, we evict a partition from the least recently accessed RDD, unless this is the same RDD as the one with the new partition. In that case, we keep the old partition in memory to prevent cycling partitions from the same RDD in and out. This is important because most operations will run tasks over an entire RDD, so it is quite likely that the partition already in memory will be needed in the future. We found this default policy to work well in all our applications so far, but we also give users further control via a "persistence priority" for each RDD.

Finally, each instance of Spark on a cluster currently has its own separate memory space. In future work, we plan to investigate sharing RDDs across instances of Spark through a unified memory manager.




a) Lines typed by user b) Resulting object graph

Figure 6: Example showing how the Spark interpreter translates two lines entered by the user into Java objects.

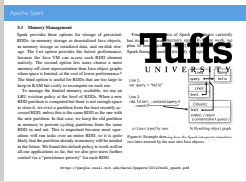
https://people.csail.mit.edu/matei/papers/2012/nsdi_spark.pdf



2019-10-21

Floorplan: Spatial Layout in Memory Management Systems

└Apache Spark



## Extras: Related Work

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1. Implementation of Immix in Rust
2. Block-structured heaps
3. GHC block descriptors
4. Quadtree layout visualization
5. Heap Layers
6. Flash Relate: Flare
7. PADS-Haskell parsing
8. LoCal location calculus





Extras: Related Work
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Tufts UNIVERSITY

## Abusing Rust

- Safety model too restrictive at times, so must use *unsafe* code
- Implementing the Line Mark Table
  - Remember the state of every line in memory
  - Map of unsigned bytes (*u8*) for every 256-bytes of memory
- Allocation: Multiple allocators may access line mark table
  - Rust array of *u8* disallows concurrent writing
- Collection: Set lines to *live* by atomically storing to a byte
  - Rust does not support Atomic unsigned bytes
- Work Around: Generalize Line Mark Table as *AddressMapTable*
- Wrap *unsafe* code into impl of *AddressMapTable*
- Rely on compiler to generate x86 Byte store which is atomic

```
pub struct AddressMapTable {
  start : Address,
  end   : Address,

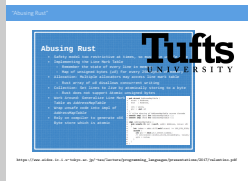
  len : usize,
  ptr : *mut u8
}
// allow sharing of AddressMapTable across threads
unsafe impl Sync for AddressMapTable {};
unsafe impl Send for AddressMapTable {};

impl AddressMapTable {
  pub unsafe fn set (&self, addr: Address, value: u8)
  {
    let index = addr.diff(self.start) >> LOG_PTR_SIZE;
    unsafe {
      let ptr = self.ptr.offset(index);
      // intrinsics::atomic_store_relaxed(ptr, value);
      *ptr = value;
    }
  }
}
```

https://www.eidos.ic.i.u-tokyo.ac.jp/~tau/lecture/programming_languages/presentations/2017/valentino.pdf







## Block-Structured Heaps

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Thus motivated, GHC's storage manager uses a block-structured heap. Although this is not a new idea [DEB94, Ste77], the literature is surprisingly thin, so we pause to describe how it works.

- The heap is divided into fixed-size B-byte blocks. Their exact size B is not important, except that it must be a power of 2. GHC uses 4kbytes blocks by default, but this is just a compile-time constant and is easily changed.
- Each block has an associated block descriptor, which describes the generation and step of the block, among other things. Any address within a block can be mapped to its block descriptor with a handful of instructions - we discuss the details of this mapping in Section 2.3.
- Blocks can be linked together, through a field in their descriptors, to form an area. For example, after garbage collection the mutator is provided with an allocation area of free blocks in which to allocate fresh objects.
- The heap contains heap objects, whose layout is shown in Figure 1. From the point of view of this paper, the important point is that the first word of every heap object, its info pointer, points to its statically-allocated info table, which in turn contains layout information that guides the garbage collector.
- A heap pointer always addresses the first word of a heap object; we do not support interior pointers.
- A large object, whose size is greater than a block, is allocated in a block group of contiguous blocks.

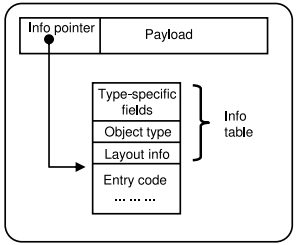
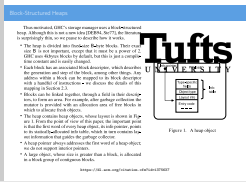



Figure 1. A heap object

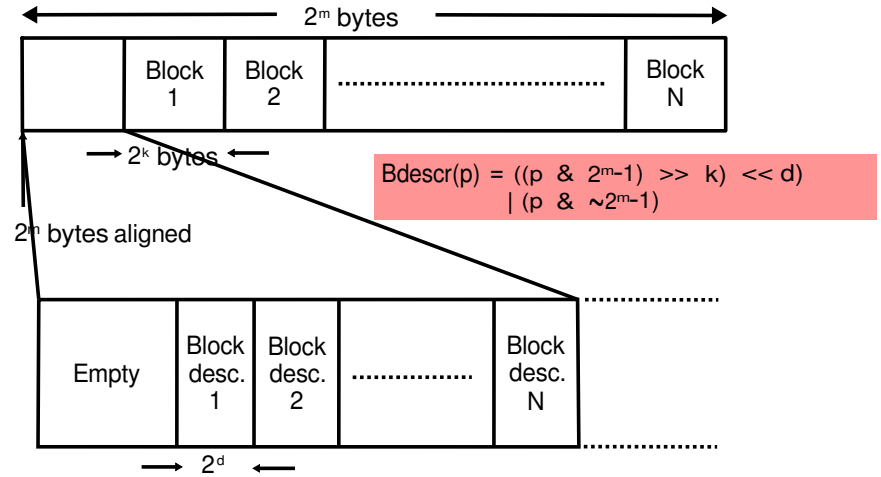
https://dl.acm.org/citation.cfm?id=1375637







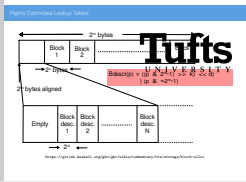
## Highly Optimized Lookup Tables




https://gitlab.haskell.org/ghc/ghc/wikis/commentary/rts/storage/block-alloc







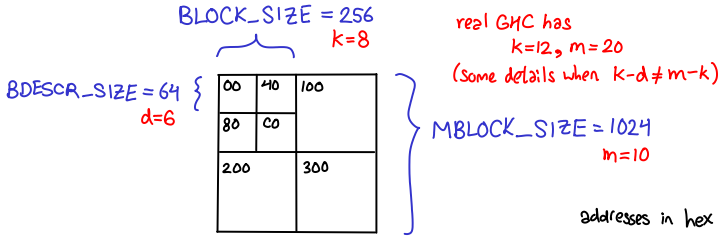
## Quadtree Layout Visualization

Tufts UNIVERSITY

THE GHC BLOCK ALLOCATOR ON A 64-BIT MACHINE (d=6)
— Edward Z. Yang

The block allocator allows us to manage our heap (and other allocations) with multiple blocks, rather than a single contiguous region. This scheme was presented in the paper "Parallel generational-copying garbage collection with a block-structured heap" and there is also some good commentary at
http://ghc.haskell.org/trac/ghc/wiki/Commentary/Rts/Storage/BlockAlloc

In this document, I want to visualize block allocation using small choices for block size and megablock size.

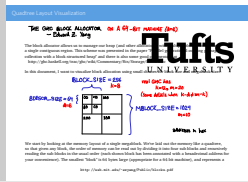


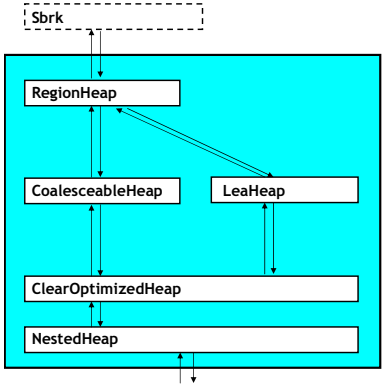

We start by looking at the memory layout of a single megablock. We've laid out the memory like a quadtree, so that given any block, the order of memory can be read out by dividing it into four sub-blocks and recursively reading the sub-blocks in the usual order (each shown block has been annotated with a hexadecimal address for your convenience). The smallest "block" is 64 bytes large (appropriate for a 64-bit machine), and represents a

http://web.mit.edu/~ezyang/Public/blocks.pdf










(b) A diagram of the heap layers that comprise our implementation of reaps. Reaps adapt to their use, acting either like regions or heaps (see Section 5). The CoalesceableHeap layer adds per-object metadata that enable a heap to subsequently manage memory obtained from a region.

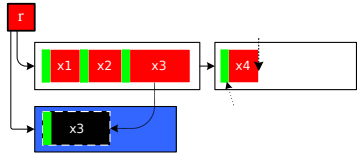


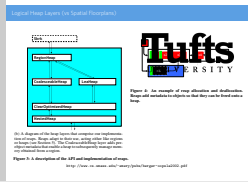

**Figure 4: An example of reap allocation and deallocation. Reaps add metadata to objects so that they can be freed onto a heap.**

**Figure 3: A description of the API and implementation of reaps.**

`http://www.cs.umass.edu/~emery/pubs/berger-oopsla2002.pdf`

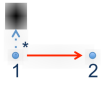






```
Node(1, "^[0-9]+$", Anchor("value", Vert(*), Horiz(0)))
Node(2, "^[0-9]+$", ⊥)
Edge(1, 2, Vert(0), Horiz(1), Select(All, All))
```

(a)




(b)

Figure 3: (a) FLARE program for first example extraction task with (b) schematic illustration. **Node** constraints are shown as dots, **Edge** constraints are shown as solid arrows, and **Anchor** constraints are shown with a dashed arrow and anchor symbol. **Edge**s and **Anchor**s of non-constant length are labeled with a Kleene star. Node numbers correspond to attribute IDs in the desired relational tuple.

| | A | B | C | D | E | ... | R |
|---|---|---|---|---|---|---|---|
| 1 | | value | year | value | year | | Comments |
| 2 | Albania | 1,000 | 1950 | 930 | 1981 | | FRA 1 |
| 3 | Austria | 3,139 | 1951 | 3,177 | 1955 | | FRA 3 |
| 4 | Belgium | 541 | 1947 | 601 | 1950 | | |
| 5 | Bulgaria | 2,964 | 1947 | 3,259 | 1958 | | FRA 1 |
| 6 | Czech ... | 2,416 | 1950 | 2,503 | 1960 | | NC |

...

(a)

```
Node(3, "^[a-zA-Z]+$", ⊥)
Node(4, "^[a-zA-Z]+$", ⊥)
Edge(3, 1, Vert(0), Horiz(*), Select(All, All))
Edge(2, 4, Vert(0), Horiz(*), Select(All, All))
```

(a)


(b)

Figure 4: (a) A set of additional constraints added to Figure 3a; (b) schematic illustration.

| | A | B | C | D |
|---|---|---|---|---|
| 1 | Albania | 1,000 | 1950 | FRA 1 |
| 2 | Albania | 930 | 1981 | FRA 1 |

...

| | | | | |
|---|---|---|---|---|
| 5 | Austria | 3,139 | 1951 | FRA 3 |
| 6 | Austria | 3,177 | 1955 | FRA 3 |

...

| | | | | |
|---|---|---|---|---|
| 9 | Belgium | 541 | 1947 | |
| 10 | Belgium | 601 | 1950 | |

...

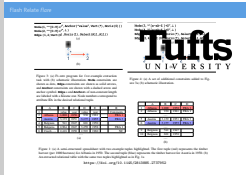
(b)

Figure 1: (a) A semi-structured spreadsheet with two example tuples highlighted. The first tuple (red) represents the timber harvest (per 1000 hectares) for Albania in 1950. The second tuple (blue) represents the timber harvest for Austria in 1950. (b) An extracted relational table with the same two tuples highlighted as in Fig. 1a

https://doi.org/10.1145/2813885.2737952







## PADS-Haskell: Layouts for Parsing [1/2]

Tufts University

```haskell
newtype MapsFile =
  MapsFile ([Line Region] terminator EOF)

data Region = Region
  {           start_addr :: Hex
  , '-',      end_addr   :: Hex
  , ' ',      perms      :: Permissions
  , ' ',      offset     :: Int
  , ' ',      device     :: (Hex, ':', Hex)
  , ' ',      inode      :: Int
  , ws ,      path       :: RegionName
  }

type Hex = StringME '[0-9A-Fa-f]+'

data RP = READ  'r' | NOREAD  '-'
data WP = WRITE 'w' | NOWRITE '-'
data XP = EXEC  'x' | NOEXEC  '-'
data SP = SHARE 's' | PRIVATE 'p'
```

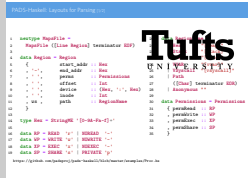
```haskell
data RegionName =
    Heap       "[heap]"
  | Stack      "[stack]"
  | VDSO       "[vdso]"
  | VVAR       "[vvar]"
  | VSyscall   "[vsyscall]"
  | Path
    ([Char] terminator EOR)
  | Anonymous ""

data Permissions = Permissions
  { permRead  :: RP
  , permWrite :: WP
  , permExec  :: XP
  , permShare :: SP
  }
```

https://github.com/padsproj/pads-haskell/blob/master/examples/Proc.hs







## PADS-Haskell: Layouts for Parsing [2/2]

Tufts University

```
00400000-00422000 r-xp 00000000 fe:02 4968                               /usr/bin/less
00622000-00623000 r--p 00022000 fe:02 4968                               /usr/bin/less
00623000-00627000 rw-p 00023000 fe:02 4968                               /usr/bin/less
00627000-0062b000 rw-p 00000000 00:00 0
00aa0000-00ac1000 rw-p 00000000 00:00 0                                  [heap]
7f1ae9999000-7f1ae99b2000 r-xp 00000000 fe:02 93235                      /usr/lib/libpthread-2.25.so
7f1ae99b2000-7f1ae9bb1000 ---p 00019000 fe:02 93235                      /usr/lib/libpthread-2.25.so
7f1ae9bb1000-7f1ae9bb2000 r--p 00018000 fe:02 93235                      /usr/lib/libpthread-2.25.so
7f1ae9bb2000-7f1ae9bb3000 rw-p 00019000 fe:02 93235                      /usr/lib/libpthread-2.25.so
7f1ae9bb3000-7f1ae9bb7000 rw-p 00000000 00:00 0
7f1ae9bb7000-7f1ae9d52000 r-xp 00000000 fe:02 93077                      /usr/lib/libc-2.25.so
7f1ae9d52000-7f1ae9f51000 ---p 0019b000 fe:02 93077                      /usr/lib/libc-2.25.so
7f1ae9f51000-7f1ae9f55000 r--p 0019a000 fe:02 93077                      /usr/lib/libc-2.25.so
7f1ae9f55000-7f1ae9f57000 rw-p 0019e000 fe:02 93077                      /usr/lib/libc-2.25.so
7f1ae9f57000-7f1ae9f5b000 rw-p 00000000 00:00 0
7f1ae9f5b000-7f1ae9fcd000 r-xp 00000000 fe:02 108084                     /usr/lib/libpcre.so.1.2.8
7f1ae9fcd000-7f1aea1cc000 ---p 00072000 fe:02 108084                     /usr/lib/libpcre.so.1.2.8
7f1aea1cc000-7f1aea1cd000 r--p 00071000 fe:02 108084                     /usr/lib/libpcre.so.1.2.8
7f1aea1cd000-7f1aea1ce000 rw-p 00072000 fe:02 108084                     /usr/lib/libpcre.so.1.2.8
7f1aea1ce000-7f1aea235000 r-xp 00000000 fe:02 106343                     /usr/lib/libncursesw.so.6.0
7f1aea235000-7f1aea434000 ---p 00067000 fe:02 106343                     /usr/lib/libncursesw.so.6.0
7f1aea434000-7f1aea438000 r--p 00066000 fe:02 106343                     /usr/lib/libncursesw.so.6.0
7f1aea438000-7f1aea43a000 rw-p 0006a000 fe:02 106343                     /usr/lib/libncursesw.so.6.0
7f1aea43a000-7f1aea45d000 r-xp 00000000 fe:02 93078                      /usr/lib/ld-2.25.so
7f1aea490000-7f1aea629000 r--p 00000000 fe:02 96759                      /usr/lib/locale/locale-archive
7f1aea629000-7f1aea62d000 rw-p 00000000 00:00 0
7f1aea65c000-7f1aea65d000 r--p 00022000 fe:02 93078                      /usr/lib/ld-2.25.so
7f1aea65d000-7f1aea65e000 rw-p 00023000 fe:02 93078                      /usr/lib/ld-2.25.so
7f1aea65e000-7f1aea65f000 rw-p 00000000 00:00 0
7fff3cc14000-7fff3cc35000 rw-p 00000000 00:00 0                          [stack]
7fff3cc3a000-7fff3cc3c000 r--p 00000000 00:00 0                          [vvar]
```



2019-10-21

Floorplan: Spatial Layout in Memory Management Systems

└PADS-Haskell: Layouts for Parsing [2/2]