Transparent Pointer Compression for Linked Data Structures

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Growth of 64-bit computing

- **64-bit architectures are increasingly common:**
  - New architectures and chips (G5, IA64, X86-64, …)
  - High-end systems have existed for many years now

- **64-bit address space used for many purposes:**
  - Address space randomization (security)
  - Memory mapping large files (databases, etc)
  - Single address space OS's
  - Many 64-bit systems have < 4GB of phys memory
    - 64-bits is still useful for its *virtual address space*

Cost of a 64-bit virtual address space

BIGGER POINTERS

- **Pointers must be 64 bits (8 bytes) instead of 32 bits:**
    - *Significant impact for pointer-intensive programs!*

- **Pointer intensive programs suffer from:**
    - Reduced effective L1/L2/TLB cache sizes
    - Reduced effective memory bandwidth
    - Increased alignment requirements, etc

- **Pointer intensive programs are increasingly common:**
    - Recursive data structures (our focus)
    - Object oriented programs

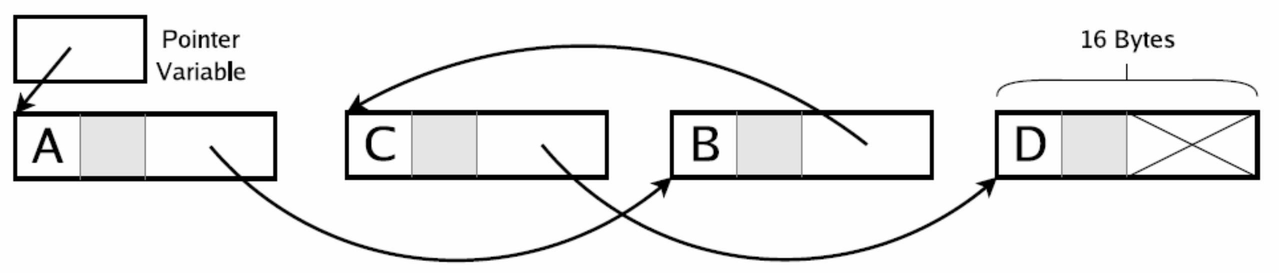
Previously Published Approaches

- **Simplest approaches: Use 32-bit addressing**
  - Compile for 32-bit pointer size “-m32”
  - Force program image into 32-bits [Adl-Tabatabai’04]
  - Loses advantage of 64-bit address spaces!
- **Other approaches: Exotic hardware support**
  - Compress pairs of values, speculating that pointer offset is small [Zhang’02]
  - Compress arrays of related pointers [Takagi’03]
  - Requires significant changes to cache hierarchy

No previous fully-automatic compiler technique to shrink pointers in RDS’s

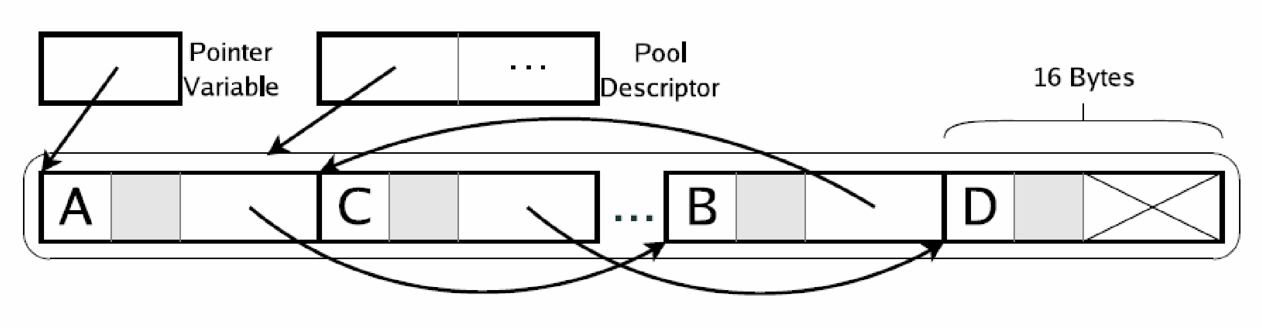
Our Approach (1/2)

Original heap layout



1. **Use Automatic Pool Allocation [PLDI'05] to partition heap into memory pools:**
   - Infers and captures pool homogeneity information

Layout after pool allocation

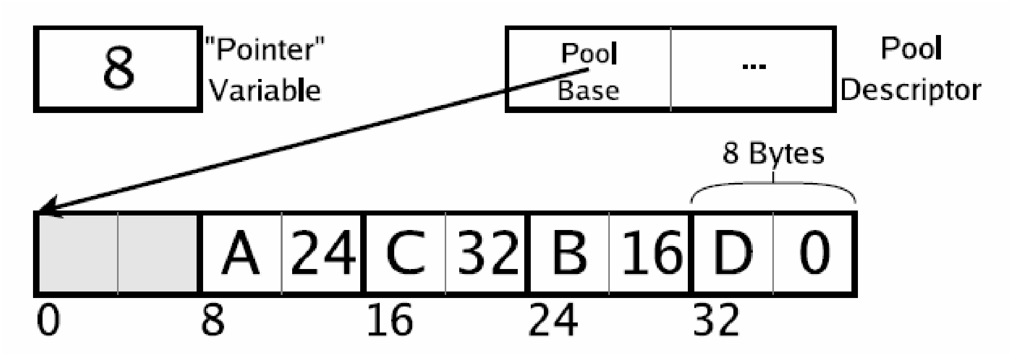


Our Approach (2/2)

2. **Replace pointers with 64-bit integer offsets from the start of the pool**
    - Change *Ptr into *(PoolBase+Ptr)

3. **Shrink 64-bit integers to 32-bit integers**
    - Allows each pool to be up to 4GB in size

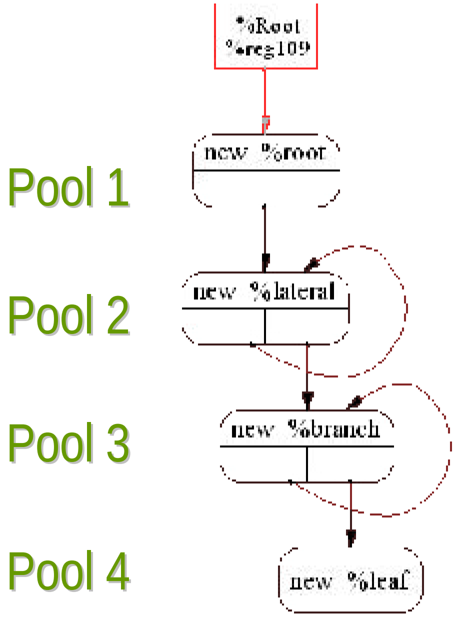
Layout after pointer compression



Talk Outline

- Introduction & Motivation
- Automatic Pool Allocation Background
- Pointer Compression Transformation
- Experimental Results
- Conclusion

Automatic Pool Allocation

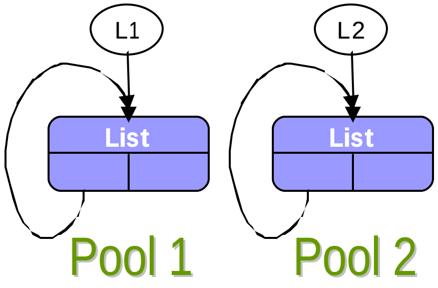


1. Compute points-to graph:

- Ensure each pointer has one target
  - "unification-based" approach

2. Infer pool lifetimes:

- Uses escape analysis



3. Rewrite program:

- malloc → poolalloc, free → poolfree
- Insert calls to poolinit/pooldestroy
- Pass pool descriptors to functions

For more info: see MSP paper or talk at PLDI tomorrow

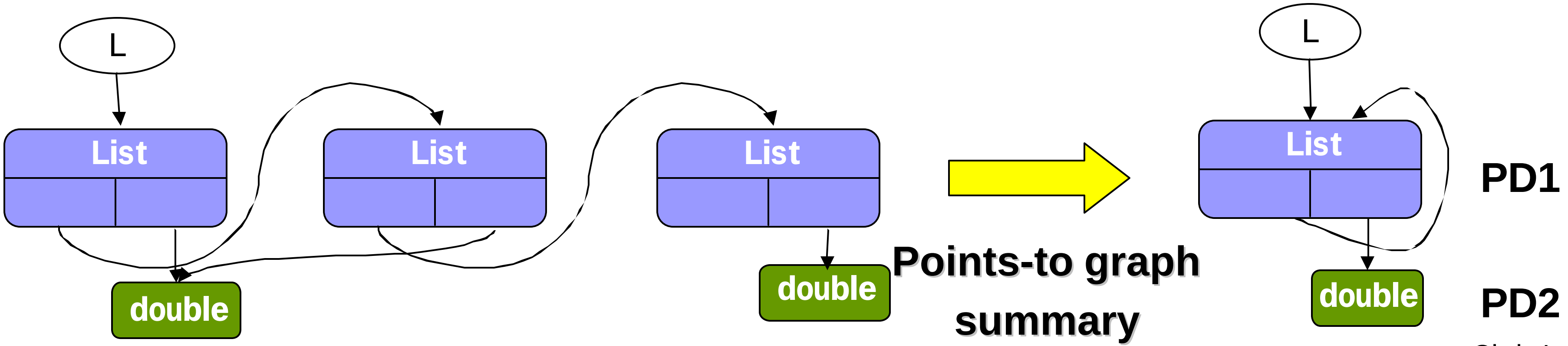
A Simple Pointer-intensive Example

- **A list of pointers to doubles**

Pool allocate

```
List *L = 0;
for (…) {
  List *N = malloc(List);
  N->Next = L;
  N->Data = malloc(double);
  L = N;
}
```

```
List *L = 0;
for (…) {
  List *N = poolalloc(PD1, List);
  N->Next = L;
  N->Data = poolalloc(PD2,double);
  L = N;
}
```

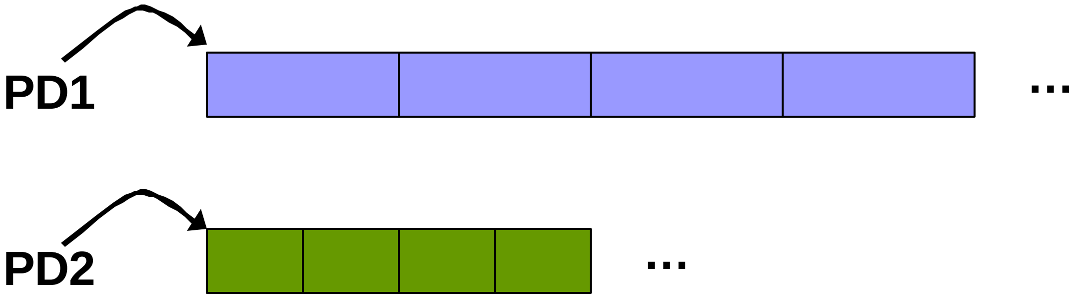


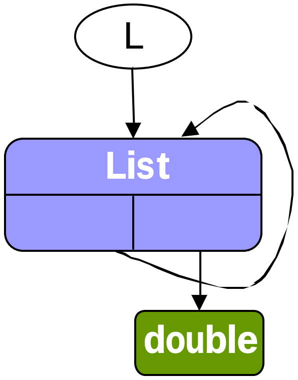
Effect of Automatic Pool Allocation 1/2

- **Heap is partitioned into separate pools**
  - Each individual pool is smaller than total heap

```
List *L = 0;
for (…) {
  List *N = malloc(List);
  N->Next = L;
  N->Data = malloc(double);
  L = N;
}
```

```
List *L = 0;
for (…) {
  List *N = poolalloc(PD1, List);
  N->Next = L;
  N->Data = poolalloc(PD2,double);
  L = N;
}
```





Effect of Automatic Pool Allocation 2/2

- **Each pool has a descriptor associated with it:**
  - Passed into poolalloc/poolfree

```
List *L = 0;
for (…) {
  List *N = malloc(List);
  N->Next = L;
  N->Data = malloc(double);
  L = N;
}
```

```
List *L = 0;
for (…) {
  List *N = poolalloc(PD1, List);
  N->Next = L;
  N->Data = poolalloc(PD2,double);
  L = N;
}
```

- **We know which pool each pointer points into:**
  - Given the above, we also have the pool descriptor
  - e.g. “**N**”, “**L**” → PD1 and **`N->Data`** → PD2

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Index Conversion of a Pool

- **Force pool memory to be contiguous:**
  - Normal PoolAlloc runtime allocates memory in chunks
  - Two implementation strategies for this (see paper)
- **Change pointers into the pool to integer offsets/indexes from pool base:**
  - Replace "`*P`" with "`*(PoolBase + P)`"

A pool can be index converted if pointers into it only point to heap memory (no stack or global mem)

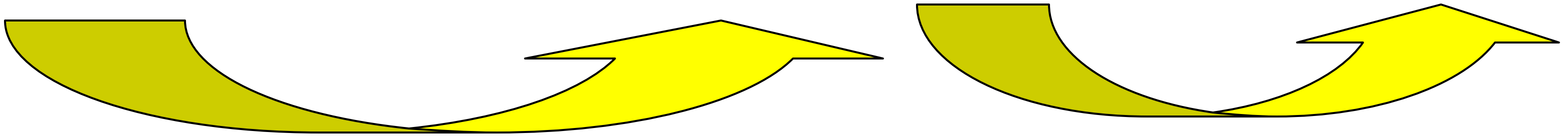
Index Compression of a Pointer

- **Shrink indexes in type-homogenous pools**
  - Shrink from 64-bits to 32-bits
- **Replace structure definition & field accesses**
  - Requires accurate type-info and type-safe accesses

```
struct List {
  struct List *Next;
  int Data;
};

List *L = malloc(16);
```

```
struct List {
  int64 Next;
  int Data;
};

L = malloc(16);
```

```
struct List {
  int32 Next;
  int Data;
};

L = malloc(8);
```

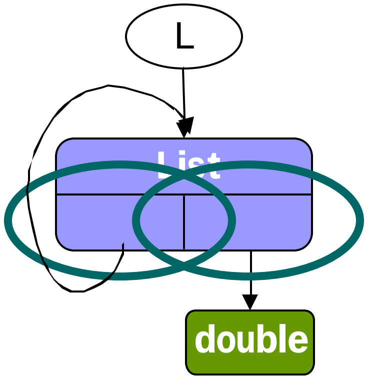


index conversion

index compression

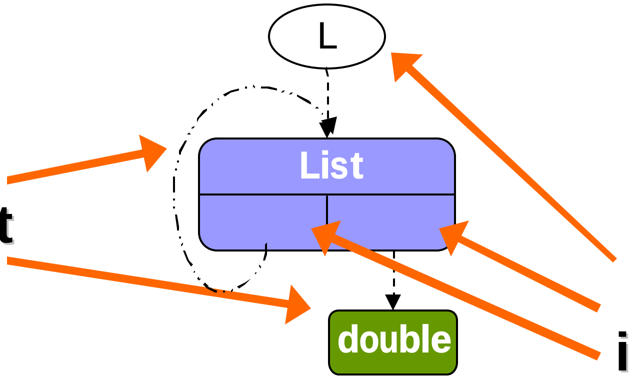
Index Conversion Example 1

Previous Example



Two pointers are compressible

After Index Conversion



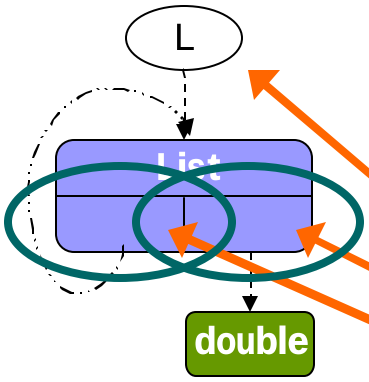
Index Convert Pools

64-bit integer indexes

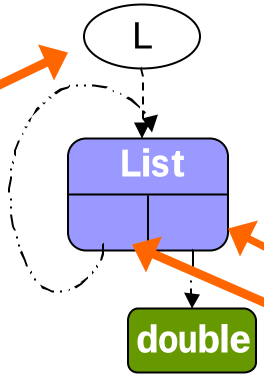
Index conversion changes pointer dereferences, but not memory layout

Index Compression Example 1

Example after index conversion



64-bit integer indices



32-bit integer indices

Compress pointers, change accesses to and size of structure

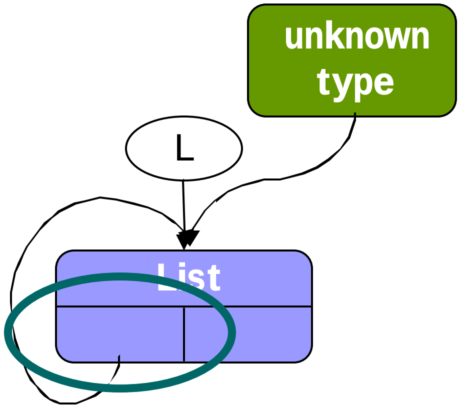
Compress both indexes from 64 to 32-bit ints

‘Pointer’ *registers* remain 64-bits

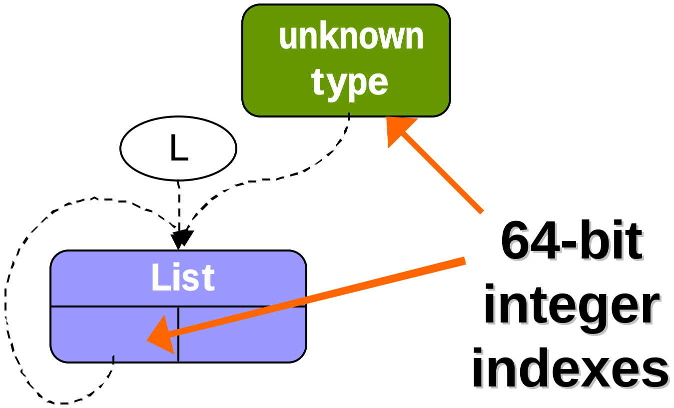
Impact of Type-Homogeneity/safety

- **Compression requires rewriting structures:**
  - e.g. malloc(32) → malloc(16)
  - Rewriting depends on type-safe memory accesses
    - We can’t know how to rewrite unions and other cases
  - Must verify that memory accesses are ‘type-safe’
- **Pool allocation infers type homogeneity:**
  - Unions, bad C pointer tricks, etc → non-TH
  - Some pools may be TH, others not
- **Can’t index compress ptrs in non-TH pools!**

Index Conversion Example 2



Heap pointer points from TH pool to a heap-only pool: compress this pointer!

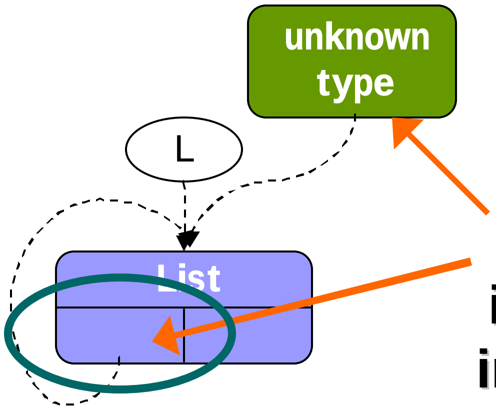


Index conversion changes pointer dereferences, but not memory layout

Compression of TH memory, pointed to by non-TH memory

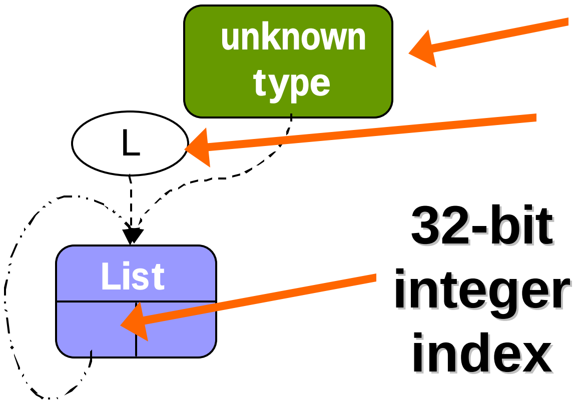
Index Compression Example 2

Example after index conversion



64-bit integer indexes

Next step: compress the pointer in the heap



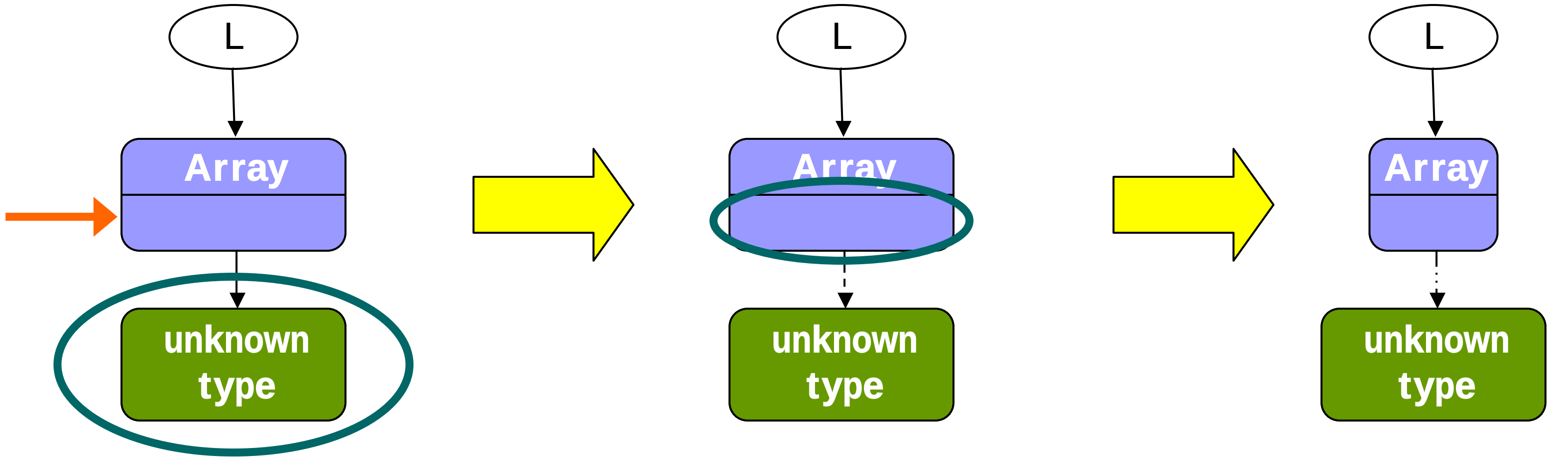
64-bit integer indexes

32-bit integer index

Compress pointer in type-safe pool, change offsets and size of structure

Compression of TH memory, pointed to by non-TH memory

Pointer Compression Example 3



Index convert non-TH pool to shrink TH pointers

Index compress array of pointers!

Compression of TH pointers, pointing to non-TH memory

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Static Pointer Compression Impl.

- **Inspect graph of pools provided by APA:**
  - Find compressible pointers
  - Determine pools to index convert
- **Use rewrite rules to ptr compress program:**
  - e.g. if P_1 and P_2 are compressed pointers, change:

$$P_1 = *P_2 \quad \Rightarrow \quad P_1' = *(\text{int}*)(\text{PoolBase}+P_2')$$

- **Perform interprocedural call graph traversal:**
  - Top-down traversal from main()

Talk Outline

- **Introduction & Motivation**
- **Automatic Pool Allocation Background**
- **Pointer Compression Transformation**
- **Dynamic Pointer Compression**
- **Experimental Results**
- **Conclusion**

Dynamic Pointer Compression Idea

- **Static compression can break programs:**
  - Each pool is limited to 2^{32} bytes of memory
    - Program aborts when 2^{32}nd byte allocated!

- **Expand pointers dynamically when needed!**
  - When 2^{32}nd byte is allocated, expand ptrs to 64-bits
  - Traverse/rewrite pool, uses type information
  - Similar to (but a bit simpler than) a copying GC pass

Dynamic Pointer Compression Cost

- **Structure offset and sizes depend on whether a pool is currently compressed:**

$P_1 = {}^*P_2 \quad \Rightarrow$

```
if (PD->isCompressed)
  P1' = *(int32*)(PoolBase + P2'*C1 + C2);
else
  P1' = *(int64*)(PoolBase + P2'*C3 + C4);
```

- **Use standard optimizations to address this:**
  - Predication, loop unswitching, jump threading, etc.

- **See paper for details**

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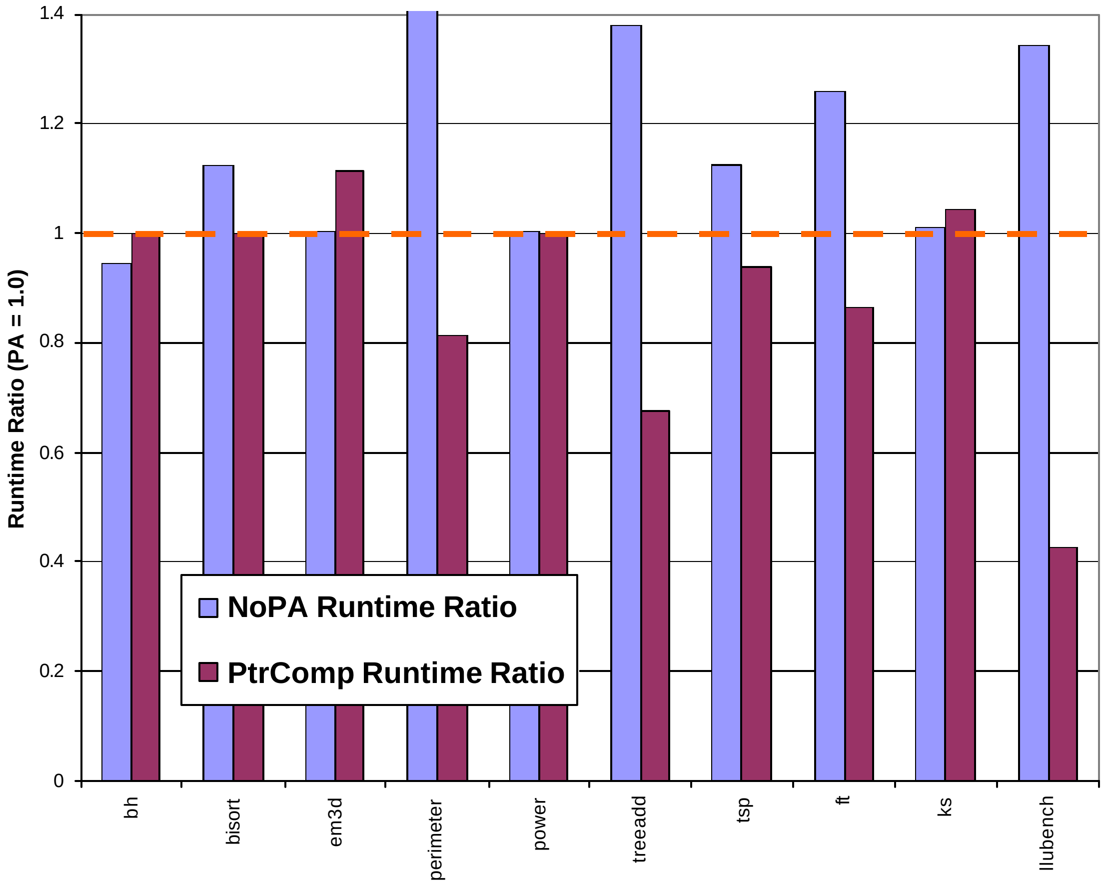
Experimental Results: 2 Questions

1. **Does Pointer Compression improve the performance of pointer intensive programs?**
    - Cache miss reductions, memory bandwidth improvements
    - Memory footprint reduction

2. **How does the impact of Pointer Compression vary across 64-bit architectures?**
    - Do memory system improvements outweigh overhead?

Static PtrComp Performance Impact

1.0 = Program compiled with LLVM & PA but no PC



Peak Memory Usage

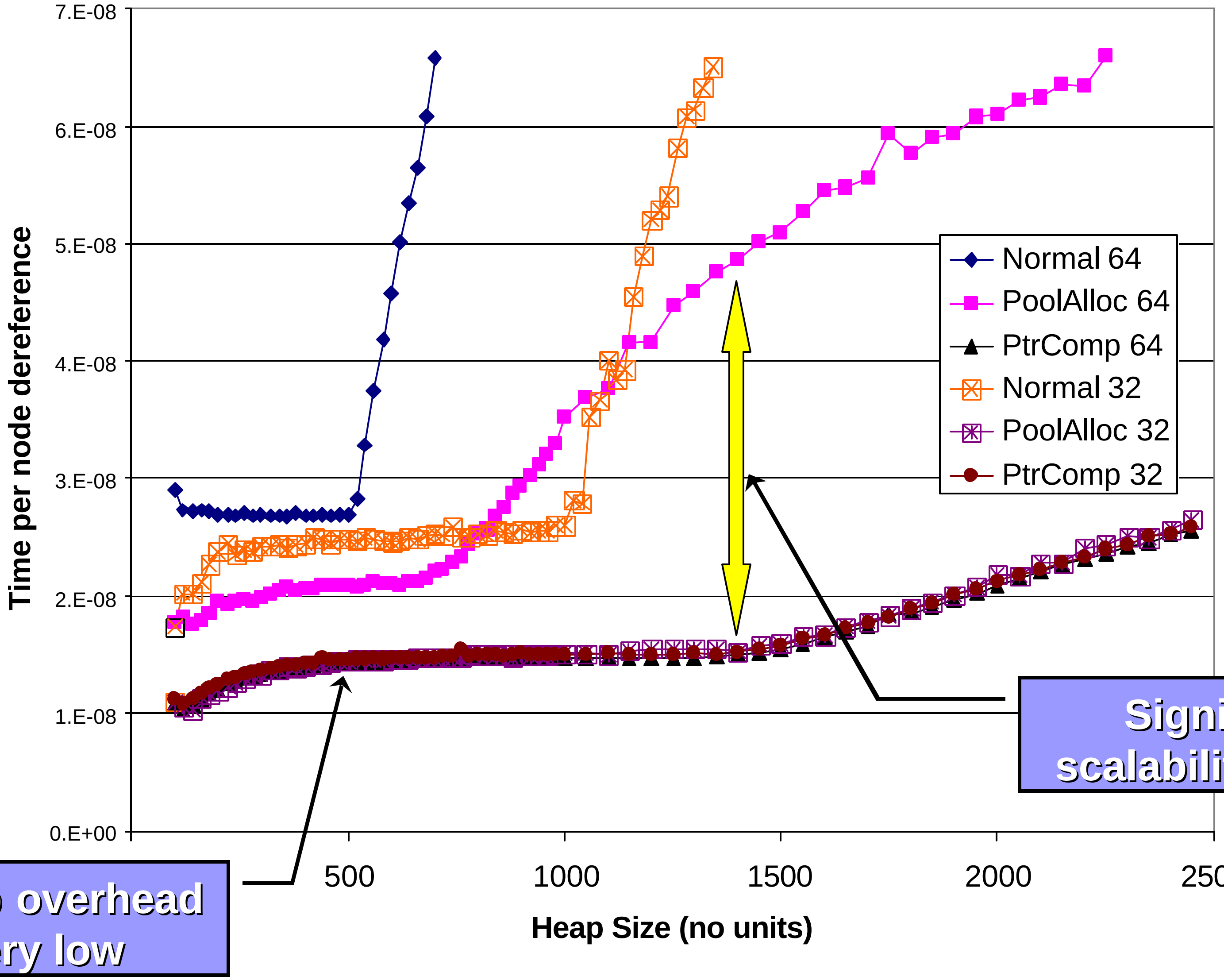
	PA	PC	PC/PA
bh	8MB	8MB	1.00
bisort	**64MB**	**32MB**	**0.50**
em3d	47MB	47MB	1.00
perimeter	**299MB**	**171MB**	**0.57**
power	882KB	816KB	0.93
treeadd	**128MB**	**64MB**	**0.50**
tsp	**128MB**	**96MB**	**0.75**
ft	**9MB**	**4MB**	**0.51**
ks	47KB	47KB	1.00
llubench	**4MB**	**2MB**	**0.50**

UltraSPARC IIIi w/1MB Cache

Evaluating Effect of Architecture

- **Pick one program that scales easily:**
  - llubench – Linked list micro-benchmark
  - llubench has little computation, many dereferences
    - Best possible case for pointer compression
- **Evaluate how ptrcomp impacts scalability:**
  - Compare to native and pool allocated version
- **Evaluate overhead introduced by ptrcomp:**
  - Compare PA32 with PC32 ('compress' 32 → 32 bits)
- **How close is ptrcomp to native 32-bit pointers?**
  - Compare to native-32 and poolalloc-32 for limit study

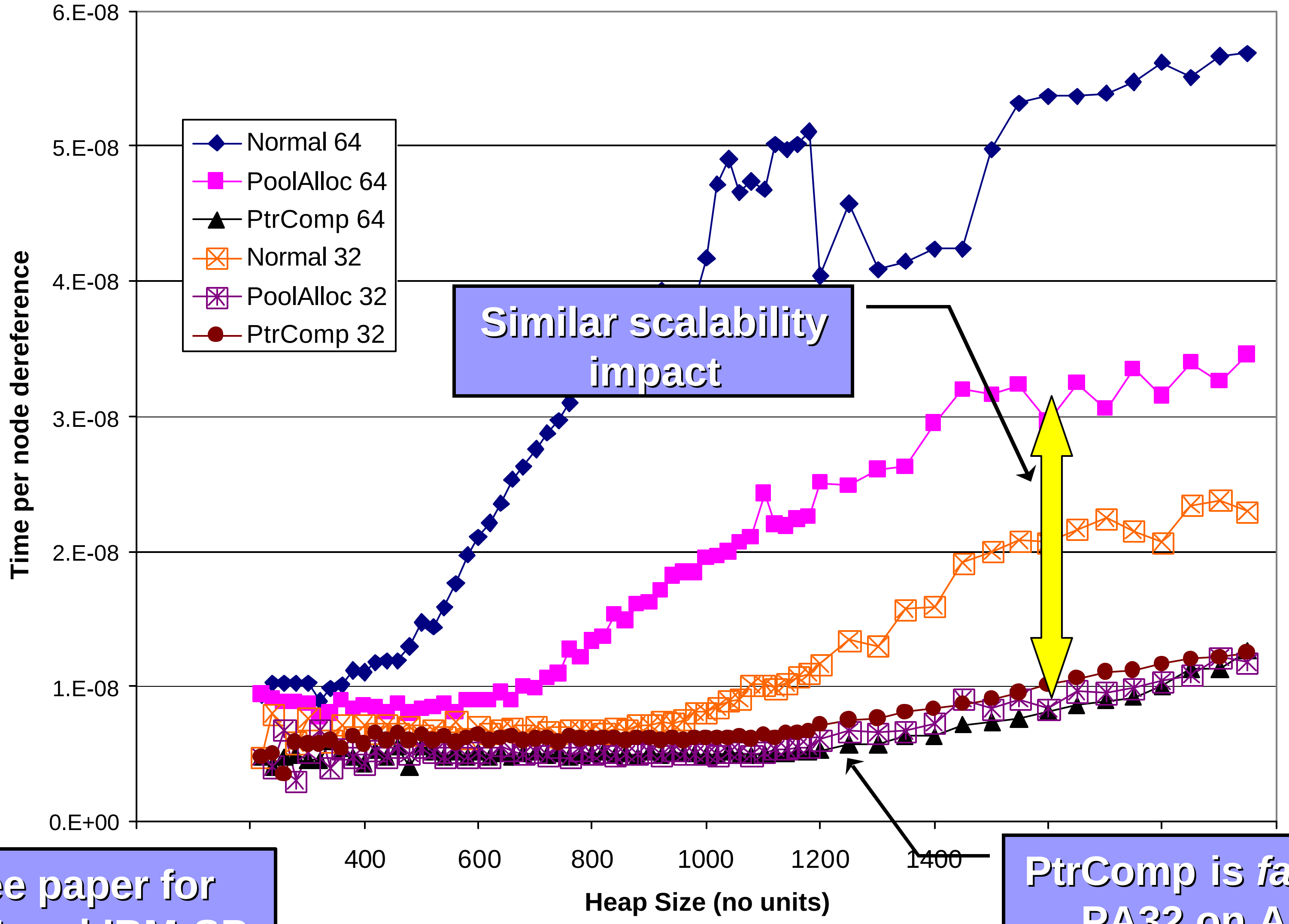
SPARC V9 PtrComp (1MB Cache)



Significant scalability impact

PtrComp overhead is very low

AMD64 PtrComp (1MB Cache)



Similar scalability impact

See paper for IA64 and IBM-SP

PtrComp is *faster* than PA32 on AMD64!

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Pointer Compression Conclusion

- **Pointer compression can substantially reduce footprint of pointer-intensive programs:**
  - … without specialized hardware support!
- **Significant perf. impact for some programs:**
  - Effectively higher memory bandwidth
  - Effectively larger caches
- **Dynamic compression for full generality:**
  - Speculate that pools are small, expand if not
  - More investigation needed, see paper!
- **Questions?**

http://llvm.cs.uiuc.edu/