

Verification of Data Layout Transformations

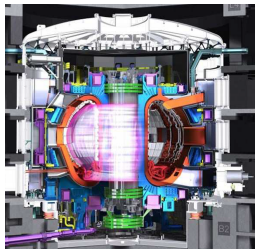
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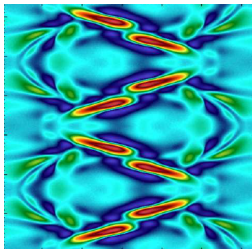
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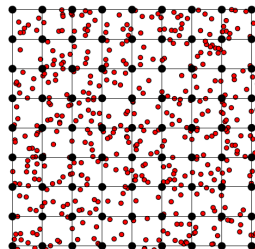
Motivating example



ITER tokamak



Plasma physics



PIC simulation

Challenges:

- Exploit data-level parallelism.
- Use domain-specific knowledge of the code.
- Do it without introducing any bugs.

Motivating example - initial code

```
typedef struct {  
    // Position  
    float x, y, z;  
    // Other fields  
    float vx, vy, vz, c, m, v;  
} particle;  
  
particle data[N];  
  
for (int i = 0; i < N; i++) {  
    // Some calculation involving data[i]  
}
```

Motivating example - splitting

Suppose that the calculation uses mainly the position.

```
typedef struct {  
    float vx, vy, vz, c, m, v;  
} cold_fields;
```

```
typedef struct {  
    float x, y, z;  
    cold_fields *other;  
} particle;
```

```
particle data[N];
```

Motivating example - peeling

Typically, cold fields are stored in a different array.

```
typedef struct {  
    float vx, vy, vz, c, m, v;  
} cold_fields;
```

```
typedef struct {  
    float x, y, z;  
} hot_fields;
```

```
cold_fields other_data[N];  
hot_fields pos_data[N];
```

Motivating example - AoS to SoA

Now, say that we want to take advantage of vector instructions.

```
typedef struct {  
    float x[N];  
    float y[N];  
    float z[N];  
} hot_fields;  
  
hot_fields pos_data;
```

Motivating example - AoS to AoSoA

But without reducing too much the locality between accesses to fields of the original struct.

```
typedef struct {  
    float x[B];  
    float y[B];  
    float z[B];  
} hot_fields;
```

```
hot_fields pos_data[ceil(N/B)];
```

Motivating example - summary

In short, the transformations we have seen are:

- Splitting.
- Peeling.
- AoS to SoA.
- AoS to AoSoA.

Motivating example - summary

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- Splitting.
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- AoS to SoA.
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E.g., when applying all these transformations, an access of the form:

`data[i].x`

becomes:

`pos_data[i/B].x[i%B]`

Project goals

- Find the basic transformations that combined give rise to the ones we are interested in.

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- Formalize a C-like language with arrays, structs and pointers.
 - Equipped with a high-level semantics, to simplify the proofs.
 - Equipped with a low-level semantics, to be closer to C.

Project goals

- Find the basic transformations that combined give rise to the ones we are interested in.
- Formalize a C-like language with arrays, structs and pointers.
 - Equipped with a high-level semantics, to simplify the proofs.
 - Equipped with a low-level semantics, to be closer to C.
- Define the transformations and prove their correctness.

Basic transformations – overview

1. Field grouping

```
// Before
typedef struct {
    int a, b, c;
} s;
```

```
// After
typedef struct {
    int b, c;
} sg;
```

```
typedef struct {
    int a; sg fg;
} s';
```

2. Array tiling

```
// Before
typedef int a[N];
```

```
// After
typedef int a'[N/B][B];
```

3. AoS to SoA

```
// Before
typedef struct {
    int a, b;
} s;
```

```
// After
typedef struct {
    int a[N]; int b[N];
} s';
```

4. Adding indirection

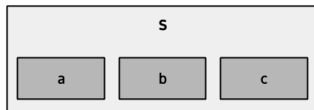
```
// Before
typedef struct {
    int a; T b;
} s;
```

```
// After
typedef struct {
    int a; T *b;
} s';
```

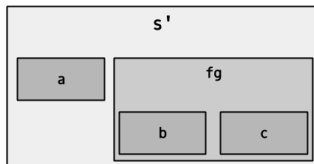
Basic transformations - grouping

1. Field grouping

```
// Before  
typedef struct {  
    int a, b, c;  
} s;
```



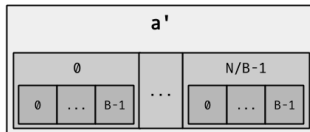
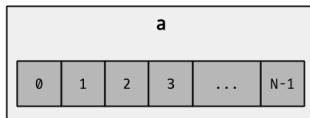
```
// After  
typedef struct {  
    int b, c;  
} sg;  
  
typedef struct {  
    int a; sg fg;  
} s';
```



Basic transformations - tiling

2. Array tiling

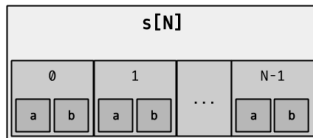
```
// Before  
typedef int a[N];  
  
// After  
typedef int a'[N/B][B];
```



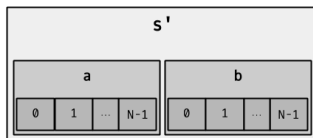
Basic transformations - AoS to SoA

3. AoS to SoA

```
// Before  
typedef struct {  
    int a, b;  
} s;
```



```
// After  
typedef struct {  
    int a[N]; int b[N];  
} s';
```

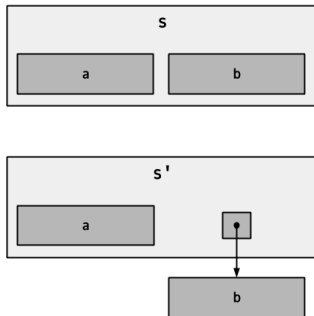


Basic transformations - indirection

4. Adding indirection

```
// Before  
typedef struct {  
    int a; T b;  
} s;
```

```
// After  
typedef struct {  
    int a; T *b;  
} s';
```



Basic transformations - justification

- **Splitting:** Field grouping and then adding indirection on the field holding the group.
- **Peeling:** Field grouping twice.
- **AoS to SoA:** AoS to SoA.
- **AoS to AoSoA:** Array tiling and then AoS to SoA on the tiles.

Language overview - values and terms

Inductive val : Type :=

- | val_error : val
- | val_unit : val
- | val_uninitialized : val
- | val_bool : bool → val
- | val_int : int → val
- | val_double : int → val
- | val_abstract_ptr : loc → accesses → val
- | val_array : typ → list val → val
- | val_struct : typ → map field val → val

Inductive trm : Type :=

- | trm_var : var → trm
- | trm_val : val → trm
- | trm_if : trm → trm → trm → trm
- | trm_let : bind → trm → trm → trm
- | trm_app : prim → list trm → trm
- | trm_while : trm → trm → trm
- | trm_for : var → val → val → trm → trm.

Language overview - primitive operations

```
Inductive prim : Type :=  
| prim_binop : binop → prim  
| prim_get : typ → prim  
| prim_set : typ → prim  
| prim_new : typ → prim  
| prim_new_array : typ → prim  
| prim_struct_access : typ → field → prim  
| prim_array_access : typ → prim  
| prim_struct_get : typ → field → prim  
| prim_array_get : typ → prim
```

Examples of the semantics of our language compared to C:

get ptr	=> *ptr	array_access ptr i	=> ptr + i
set ptr v	=> *ptr = v	struct_access ptr f	=> &(ptr->f)
new T	=> malloc(sizeof(T))	struct_get s f	=> s.f

where pointers are represented as pairs:

(l, (access_field T f)::(access_array T' i)::nil)

which would correspond to the address:

l + field_offset(f) + i * sizeof(T')

Language overview - semantics

Some crucial definitions:

Definition $\text{typdefctx} := \text{map typvar typ}.$

Definition $\text{stack} := \text{Ctx.ctx val}.$

Definition $\text{state} := \text{map loc val}.$

Language overview - semantics

Some crucial definitions:

Definition $\text{typdefctx} := \text{map typvar typ}.$

Definition $\text{stack} := \text{Ctx.ctx val}.$

Definition $\text{state} := \text{map loc val}.$

And the relation that defines the big-step reduction rules:

Inductive $\text{red} : \text{typdefctx} \rightarrow \text{stack} \rightarrow \text{state} \rightarrow \text{trm} \rightarrow \text{state} \rightarrow \text{val} \rightarrow \text{Prop}$

Language overview - typing

The allowed types are:

```
Inductive typ : Type :=  
| typ_unit : typ  
| typ_int : typ  
| typ_double : typ  
| typ_bool : typ  
| typ_ptr : typ → typ  
| typ_array : typ → option size → typ  
| typ_struct : map field typ → typ  
| typ_var : typvar → typ.
```

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  | typ_struct : map field typ → typ  
  | typ_var : typvar → typ.
```

With their corresponding definitions (analogous to stack and state):

Definition gamma := Ctx.ctx typ.

Definition phi := map loc typ.

Language overview - typing

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  | typ_ptr : typ → typ  
  | typ_array : typ → option size → typ  
  | typ_struct : map field typ → typ  
  | typ_var : typvar → typ.
```

With their corresponding definitions (analogous to stack and state):

```
Definition gamma := Ctx.ctx typ.
```

```
Definition phi := map loc typ.
```

Typing is defined as the following relation:

```
Inductive typing : typdefctx → gamma → phi → trm → typ → Prop
```

Language overview - properties

For memory accesses, we know the type of the data being manipulated:

```
Inductive typing_val (C:typdefctx) (f:phi) : val → typ → Prop :=  
  | typing_val_abstract_ptr : ∀ l p T,  
    read_phi C f l p T →  
    typing_val C f (val_abstract_ptr l p) (typ_ptr T)
```

```
Inductive typing (C:typdefctx) : gamma → phi → trm → typ → Prop :=  
  | typing_get : ∀ G f T t1,  
    typing C G f t1 (typ_ptr T) →  
    typing C G f (trm_app (prim_get T) (t1::nil)) T
```

Typing result for full execution:

```
Theorem type_soundness : ∀ C m t v T,  
  red C empty_stack empty_state t m v →  
  typing C empty_gamma empty_phi t T →  
  ~is_error v →  
  ∃ f, typing_val C f v T  
  ∧ state_typing C f m.
```

Field grouping

The arguments of the transformation are:

- The struct name Ts.
- The fields b and c (fs).
- The new struct name Tg.
- The new field fg.

```
// Before
typedef struct {
    int a, b, c;
} Ts;
```

```
// After
typedef struct {
    int b, c;
} Tg;
```

```
typedef struct {
    int a; Tg fg;
} Ts;
```

Field grouping

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// After
typedef struct {
    int b, c;
} Tg;
```

```
typedef struct {
    int a; Tg fg;
} Ts;
```

These are used to define a transformation for:

- | | | |
|-----------|-------------|--------------|
| • terms, | • accesses, | • states and |
| • values, | • contexts, | • stacks. |

Field grouping - terms

We start with the transformation of the source code. In particular, we look at the struct access case:

```
Inductive tr_trm (gt:group_tr) : trm → trm → Prop :=  
| tr_trm_struct_access_group : ∀fs Ts fg Tg f op0 t1 op2 op1 t1',  
  gt = make_group_tr Ts fs Tg fg →  
  f ∈ fs →  
  (* The access s.f *)  
  op0 = prim_struct_access (typ_var Ts) f →  
  (* The access s'.fg.f *)  
  op1 = prim_struct_access (typ_var Ts) fg →  
  op2 = prim_struct_access (typ_var Tg) f →  
  tr_trm gt t1 t1' →  
  tr_trm gt (trm_app op0 (t1::nil)) (trm_app op2 ((trm_app op1 (t1'::nil))::nil))
```

Field grouping - values

Values need to be changed in the source code. For instance, if we look at the interesting case:

```
Inductive tr_val (gt:group_tr) : val → val → Prop :=  
  | tr_val_struct_group : ∀Ts Tg s s' fg fs sg,  
    gt = make_group_tr Ts fs Tg fg →  
    fs ⊆ dom s →  
    fg ∉ dom s →  
    dom s' = (dom s \ - fs) ∪ {fg} →  
    dom sg = fs →  
    (* Contents of the grouped fields. *)  
    s'[fg] = val_struct (typ_var Tg) sg →  
    (∀ f ∈ dom sg, tr_val gt s[f] sg[f]) →  
    (* Contents of the rest of the fields. *)  
    (∀ f ∈ dom s \ fs, tr_val gt s[f] s'[f]) →  
    tr_val gt (val_struct (typ_var Ts) s) (val_struct (typ_var Ts) s')
```

And in the stack and the memory so, from `tr_val`, we naturally define `tr_stack` and `tr_state`.

Field grouping - accesses

For accesses, if we look at the interesting case:

```
Inductive tr_accesses (gt:group_tr) : accesses → accesses → Prop :=  
| tr_accesses_field_group : ∀Ts fs fg Tg f a0 p a1 a2 p',  
  gt = make_group_tr Ts fs Tg fg →  
  f ∈ fs →  
  (* The access s.f *)  
  a0 = access_field (typ_var Ts) f →  
  (* Becomes s'.fg.f *)  
  a1 = access_field (typ_var Ts) fg →  
  a2 = access_field (typ_var Tg) f →  
  tr_accesses gt p p' →  
  tr_accesses gt (a0::p) (a1::a2::p')
```

This is used in:

```
Inductive tr_val (gt:group_tr) : val → val → Prop :=  
| tr_val_abstract_ptr : ∀l p p',  
  tr_accesses gt p p' →  
  tr_val gt (val_abstract_ptr l p) (val_abstract_ptr l p')
```

Field grouping - typdefctx

We ‘update’ the type definitions context as follows:

```
Inductive tr_typdefctx (gt:group_tr) : typdefctx → typdefctx → Prop :=
| tr_typdefctx_intro : ∀Tfs Tfs' Tfsg Ts fs Tg fg C C',
  gt = make_group_tr Ts fs Tg fg →
  Ts ∈ dom C →
  dom C' = dom C ∪ {Tg} →
  (* The original map from fields to types. *)
  C[Ts] = typ_struct Tfs →
  (* The map for the new struct and for the grouped fields. *)
  tr_struct_map gt Tfs Tfs' Tfsg →
  C'[Ts] = typ_struct Tfs' →
  C'[Tg] = typ_struct Tfsg →
  (* The other type variables stay the same. *)
  (∀ T ∈ dom C \ {Ts}, C'[T] = C[T]) →
  tr_typdefctx gt C C'.
```


Field grouping - sanity checks

We need a way of checking that the transformation is well-defined.

```
Inductive group_tr_ok : group_tr → typdefctx → Prop :=  
| group_tr_ok_intros : ∀Tfs Ts fs fg Tg gt C,  
  gt = make_group_tr Ts fs Tg fg →  
  Ts ∈ dom C →  
  (* The struct Ts can be transformed. *)  
  C[Ts] = typ_struct Tfs →  
  Tg ∉ dom C →  
  fs ⊆ dom Tfs →  
  fg ∉ dom Tfs →  
  (* Ts doesn't appear anywhere else in the typdefctx. *)  
  (∀ Tv ∈ dom C, ~free_typvar C Tt C[Tv]) →  
  group_tr_ok gt C.
```

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  gt = make_group_tr Ts fs Tg fg →  
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  (* The struct Ts can be transformed. *)  
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  Tg ∉ dom C →  
  fs ⊆ dom Tfs →  
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Regardless of `group_tr`, we need to check that everything is well-formed:

- The `typdefctx` is well-formed if the type definitions are productive.

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  gt = make_group_tr Ts fs Tg fg →  
  Ts ∈ dom C →  
  (* The struct Ts can be transformed. *)  
  C[Ts] = typ_struct Tfs →  
  Tg ∉ dom C →  
  fs ⊆ dom Tfs →  
  fg ∉ dom Tfs →  
  (* Ts doesn't appear anywhere else in the typdefctx. *)  
  (∀ Tv ∈ dom C, ~free_typvar C Tt C[Tv]) →  
  group_tr_ok gt C.
```

Regardless of `group_tr`, we need to check that everything is well-formed:

- The `typdefctx` is well-formed if the type definitions are productive.
- Terms, values, stacks and states are well-formed if all the types that appear in them exist.

Field grouping - theorem

In the end the theorem that we prove for full executions is:

Theorem `red_tr`: $\forall gt\ C\ C'\ t\ t'\ v\ m,$
`red C empty_stack empty_state t m v` \rightarrow
`~is_error v` \rightarrow
`group_tr_ok gt C` \rightarrow
`tr_typdefctx gt C C'` \rightarrow
`tr_trm gt t t'` \rightarrow
`wf_typdefctx C` \rightarrow
`wf_trm C t` \rightarrow
 $\exists v'\ m',\ tr_val\ gt\ v\ v'$
 $\wedge\ tr_state\ gt\ m\ m'$
 $\wedge\ red\ C'\ empty_stack\ empty_state\ t'\ m'\ v'.$

Field grouping - induction

To make the proof work we strengthen it as follows:

Theorem `red_tr_ind`: $\forall \text{gt } C \ C' \ t \ t' \ v \ S \ S' \ m1 \ m1' \ m2,$
`red C S m1 t m2 v` \rightarrow
`~is_error v` \rightarrow
`group_tr_ok gt C` \rightarrow
`tr_typdefctx gt C C'` \rightarrow
`tr_trm gt t t'` \rightarrow
`tr_stack gt S S'` \rightarrow
`tr_state gt m1 m1'` \rightarrow
`wf_typdefctx C` \rightarrow
`wf_trm C t` \rightarrow
`wf_stack C S` \rightarrow
`wf_state C m1` \rightarrow
 $\exists v' \ m2', \quad \text{tr_val gt } v \ v'$
 $\wedge \text{tr_state gt } m2 \ m2'$
 $\wedge \text{red } C' \ S' \ m1' \ t' \ m2' \ v'.$

Array tiling

We need to know:

- The name of the array being changed (T_a).
- The new name for the tiles (T_t).
- The size of the tiles (K).

Array tiling

We need to know:

- The name of the array being changed (Ta).
- The new name for the tiles (Tt).
- The size of the tiles (K).

Similarly, we also define:

- `tiling_tr_ok`,
- `tr_typdefctx`,
- `tr_accesses`,
- `tr_val`,
- `tr_stack`,
- `tr_state` and
- `tr_trm`.

In this case, we change all the instances of `t[i]` to `t[i/K][i%K]` where `t` has type `typ_var Ta`.

Array tiling - some specifics

We use:

- I for the length of the original array,
- J for the length of the array of tiles and
- K for the length of the tile.

These are related by the definitions:

Definition $\text{nb_tiles } (K \ I \ J:\text{int}) : \text{Prop} :=$
 $J = I / K + \text{If } (I \bmod K = 0) \text{ then } 0 \text{ else } 1.$

Definition $\text{tiled_indices } (I \ J \ K \ i \ j \ k:\text{int}) : \text{Prop} :=$
 $i = j * K + k$
 $\wedge \text{index } I \ i$
 $\wedge \text{index } J \ j$
 $\wedge \text{index } K \ k.$

Array tiling - key components

The crucial case of `tr_val` from the array `aI` to `aJ` is captured by:

$$\begin{aligned} \forall i\ j\ k\ aK, \quad & \text{tiled_indices } I\ J\ K\ i\ j\ k \rightarrow \\ & aJ[j] = (\text{val_array } (\text{typ_var } Tt) aK) \rightarrow \\ & \text{tr_val } tt\ aI[i]\ aK[k] \end{aligned}$$

Array tiling - key components

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$$\begin{aligned} \forall i \ j \ k \ aK, \quad & \text{tiled_indices } I \ J \ K \ i \ j \ k \rightarrow \\ & aJ[j] = (\text{val_array } (\text{typ_var } Tt) \ aK) \rightarrow \\ & \text{tr_val } tt \ aI[i] \ aK[k] \end{aligned}$$

For the translation accesses and primitive operations, the aim is for all the accesses of the form:

$$l1 \ ++ \ (\text{access_array } (\text{typ_var } Ta) \ i) :: l2$$

to be transformed to:

$$l1 \ ++ \ (\text{access_array } (\text{typ_var } Ta) \ (i/K)) :: (\text{access_array } (\text{typ_var } Tt) \ (i \bmod K)) :: l2.$$

AoS to SoA

For this transformation, we need to know:

- The name of the array being changed (Ta).
- The fields names and types of the struct being changed (Tfs).
- The size of the array (K).

AoS to SoA

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- The name of the array being changed (Ta).
- The fields names and types of the struct being changed (Tfs).
- The size of the array (K).

This transformation is similar to array tiling in many ways. One key difference is that the accesses of the form:

```
l1 ++ (access_array Ta i)::(access_field (typ_struct Tfs) f)::l2
```

are transformed to:

```
l1 ++ (access_field Ta f)::(access_field (typ_array Tfs[f] K) i)::l2.
```

High-level transformations - summary

So far we have presented:

- Field grouping.
- Array tiling.
- AoS to SoA.

High-level transformations - summary

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The correctness of these is proved!

(up to a couple axioms, e.g., results on the modulo operation)

High-level transformations - summary

So far we have presented:

- Field grouping.
- Array tiling.
- AoS to SoA.

The correctness of these is proved!

(up to a couple axioms, e.g., results on the modulo operation)

Problem: This might all be just a hack if we don't link it with a more concrete, CompCert-style semantics...

High-level to low-level transformation

The grammar is extended with:

```
Inductive val : Type :=  
| val_concrete_ptr : loc → val  
| val_words : list word → val.
```

```
Inductive prim : Type :=  
| prim_ll_get : typ → prim  
| prim_ll_set : typ → prim  
| prim_ll_new : typ → prim  
| prim_ll_access : typ → prim.
```


High-level to low-level transformation

The grammar is extended with:

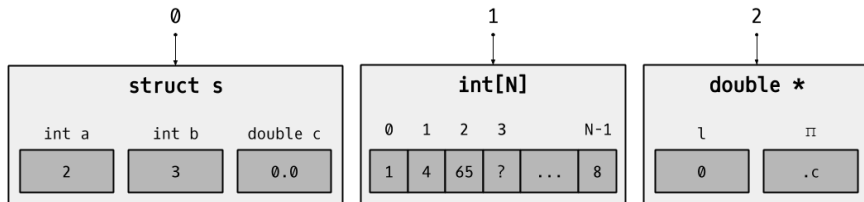
```
Inductive val : Type :=  
  | val_concrete_ptr : loc → val  
  | val_words : list word → val.
```

```
Inductive prim : Type :=  
  | prim_ll_get : typ → prim  
  | prim_ll_set : typ → prim  
  | prim_ll_new : typ → prim  
  | prim_ll_access : typ → prim.
```

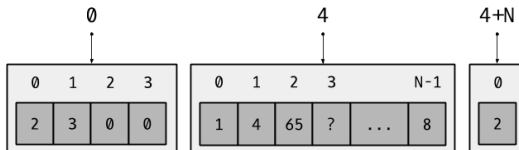
There are two sides of this transformation:

- The memory.
- The programs.

High-level to low-level transformation - memory



High-level memory.



Low-level memory.

High-level to low-level transformation - program

The values in the source code are all kept the same except for pointers:

```
Inductive tr_val (C:typdefctx) (LLC:ll_typdefctx) (a:alpha) : val → val → Prop :=  
  | tr_val_abstract_ptr : ∀ p l o,  
    tr_ll_accesses C LLC p o →  
    tr_val C LLC a (val_abstract_ptr l p) (val_concrete_ptr (a[l] + o)).
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For terms, as an example, a term:

```
trm_app (prim_struct_access T f) (t::nil)
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gets translated to:

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trm_app (prim_ll_access T[f]) (t'::(field_offset T f)::nil).
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The semantics of `prim_ll_access` is, in fact, that of addition.

High-level to low-level transformation - LLC

The low-level context is defined as follows:

```
Record ll_typdefctx := make_ll_typdefctx {  
  typvar_sizes    : map typvar size;  
  fields_offsets  : map typvar (map field offset);  
  fields_order    : map typvar (list field) }.
```

We need to ensure coherency between the type definition context (C) and the low-level context (LLC). In particular:

- The type variable sizes in LLC match with the types in C.
- The field offsets match with the order of the fields and the sizes of each of their types.

High-level to low-level transformation - theorem

The goal is to prove:

Theorem `red_tr_warmup` : $\forall C \text{ LLC } T \text{ m a v t' m' v' ,}$
 `red C LLC empty_stack empty_state t m v` \rightarrow
 `typing C empty_gamma empty_phi t T` \rightarrow
 `~is_error v` \rightarrow
 `ll_typdefctx_ok C LLC` \rightarrow
 `tr_trm C LLC a t t'` \rightarrow
 `wf_typdefctx C` \rightarrow
 `wf_trm C t` \rightarrow
 `wf_typ C T` \rightarrow
 $\exists v' m' , \text{ tr_state } C \text{ LLC a m m'}$
 $\wedge \text{ tr_val } C \text{ LLC a v v'}$
 $\wedge \text{ red } C \text{ LLC empty_stack empty_state t' m' v' .$

Project extent

Accomplished goals:

- Defined a high-level language convenient to argue about data-layout transformations.

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- Basically proved the correctness of:
 - Field grouping.
 - Array tiling.
 - AoS to SoA.

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- Defined a high-level language convenient to argue about data-layout transformations.
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- Basically proved the correctness of:
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Some statistics:

lines of spec	lines of proof	lines of comments
2723	3103	668

Future work

Next steps:

- Formalization of the transformation ‘adding indirection’.
- Realizations of the transformations as functions.
- Some arithmetic results in the tiling and low-level transformations.
- Work on loops and add loop transformations.
- Connect the low-level language with CompCert (at which level?)

Thanks!