Enhancing spatial safety: fixing thousands of -Wflex-array-member-not-at-end warnings

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Kernel Recipes
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Who am I?

By @shidokou

Who am I?

- **Upstream first** – 8 years.
- Upstream Linux Kernel Engineer.
    - Kernel hardening.
    - Proactive security.

- Kernel Self-Protection Project (**KSPP**).
- Google Open Source Security Team (**GOSST**).
    - Linux Kernel division.

By @shidokou

Agenda

- **Introduction**
  - C99 flexible-array members (FAMs)
  - The new -Wflex-array-member-not-at-end compiler option
- **The challenge of -Wflex-array-member-not-at-end**
  - What’s wrong with FAMs in the middle?
  - How did we get here? - A brief history
  - Fixing thousands of -Wfamnae warnings
- **Conclusions**

Quick review of C99 flexible-array members

- The last member of a struct.

```
struct flex {
    ...
    size_t  count;
    struct foo fam[];
};
```

Extended review of C99 flexible-array members

- The last member of a struct.
- The flex struct usually contains a ***counter*** member.

```
struct flex {
    ...
    size_t  count;
    struct foo fam[];
};
```

Extended review of C99 flexible-array members

- The last member of a struct.
- The flex struct usually contains a ***counter*** member.
- `struct flex` may not be a member of another struct.

```
struct flex {
    ...
    size_t count;
    struct foo fam[];
};
```

Extended review of C99 flexible-array members

- The last member of a struct.
- The flex struct usually contains a ***counter*** member.
- `struct flex` may not be a member of another struct.

```
struct flex {
    ...
    size_t  count;
    struct foo fam[] __counted_by(count);
};
```

Extended review of C99 flexible-array members

- The last member of a struct.
- The flex struct usually contains a ***counter*** member.
- `struct flex` may not be a member of another struct.
- Run-time bounds-checking coverage on FAMs.

```
struct flex {
    ...
    size_t count;
    struct foo fam[] __counted_by(count);
};
```

The new -Wflex-array-member-not-at-end

- Developed by Qing Zhao last year (2023)
- Released in GCC 14

The new -Wflex-array-member-not-at-end

– Warns about FAMs in the middle of composite structs.

```
struct flex {
    ...
    size_t count;
    struct foo fam[] __counted_by(count);
};

struct composite {
    ...

    struct flex middle;


    ...
};
```

The new -Wflex-array-member-not-at-end

– Warns about FAMs in the middle of composite structs.

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The new -Wflex-array-member-not-at-end

– Warns about FAMs in the middle of composite structs.

```
struct flex {
    ...
    size_t count;
    struct foo fam[] __counted_by(count);
};

struct composite {
    ...

    struct flex middle; /* -Wfamnae warning! */

    ...
};
```

The challenge of enabling **-Wflex-array-member-not-at-end**

What’s wrong with FAMs in the middle?

- Flex struct in a composite struct is an extension.

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- Flex struct in a composite struct is an extension.
  - the last member

```
struct composite {
   ...

   struct flex last;
};
```

What’s wrong with FAMs in the middle?

- Flex struct in a composite struct is an extension.
  - the last member
  - **not the last member**

```
struct composite {
    ...

    struct flex last;
};
```

```
struct composite {
    ...

    struct flex middle;

    ...
};
```

What’s wrong with FAMs in the middle?

- Flex struct in a composite struct is an extension.
  - the last member
  - **not the last member – This is deprecated now.**

```
struct composite {
   ...

   struct flex last;
};
```

```
struct composite {
   ...

   struct flex middle;

   ...
};
```

What’s wrong with FAMs in the middle?

- Flex struct in a composite struct is an extension.
  - the last member
  - **not the last member – This is deprecated now.**

```
struct composite {
    ...

    struct flex last;
};
```

```
struct composite {
    ...

    struct flex middle;


    ...
};
```

What’s wrong with FAMs in the middle?

– “Compilers do not handle such a case consistently. Any code relying on this case should be modified to **ensure that flexible array members only end up at the ends of structures.**” -GCC Docs.

```
struct composite {
    ...

    struct flex middle;

    ...
};
```

How did we get here? - A brief history

- Flexible-Array Transformations - [1] & [0] to C99 [ ]
    - It took us 5 years (2019 – 2024)

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- Flexible-Array Transformations - [1] & [0] to C99 [ ]
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- [1], [0], [ ] & [N] trailing arrays & fortified memcpy()
  - Fixed __builtin_object_size()
  - Fixed __builtin_dynamic_object_size()

How did we get here? - A brief history

- Flexible-Array Transformations - [1] & [0] to C99 [ ]
  - It took us 5 years (2019 – 2024)
- [1], [0], [ ] & [N] trailing arrays & fortified memcpy()
  - Fixed __builtin_object_size()
  - Fixed __builtin_dynamic_object_size()
  - -fstrict-flex-arrays[=n] – Clang 16 & GCC 13
  - -fstrict-flex-arrays=3 enabled in Linux 6.5
    - Only C99 FAMs are considered flex arrays or VLOs.

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How did we get here? - A brief history

- The *counted_by* attribute – Clang 18 & GCC 15
  - Use __builtin_dynamic_object_size() in fortified memcpy().
  - *counted_by* annotations in progress.
  - Ideally, every FAM should be annotated.

Fixing thousands of -Wfamnae warnings in Linux

- A bit more than 60,000 warnings in total

```
struct flex {
    ...
    size_t count;
    struct foo fam[] __counted_by(count);
};

struct composite {
    ...
    struct flex middle; /* -Wfamnae warning */
    ...
};
```

Fixing thousands of -Wfamnae warnings in Linux

- A bit more than 60,000 warnings in total – 650 unique ones.

```
struct flex {
	...
	size_t count;
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struct composite {
	...
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};
```

Fixing thousands of -Wfamnae warnings in Linux

- A bit more than 60,000 warnings in total – 650 unique ones.
- Some patterns emerged.

```
struct flex {
    ...
    size_t count;
    struct foo fam[] __counted_by(count);
};

struct composite {
    ...
    struct flex middle; /* -Wfamnae warning */
    ...
};
```

-Wflex-array-member-not-at-end

Case 1: **FAMs not used at all.**

-Wflex-array-member-not-at-end

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```
struct wl1251_cmd_header {
    u16 id;
    u16 status;
    /* payload */
    u8 data[];
 } __packed;


struct cmd_read_write_memory {
        struct wl1251_cmd_header header; /* -Wfamnae warning */

        u32 addr;
        u32 size;
        u8 value[MAX_READ_SIZE];
} __packed;
```

-Wflex-array-member-not-at-end

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-Wflex-array-member-not-at-end

- Case 1: **FAMs not used at all**.
  - f4b09b29f8b4 (“wifi: ti: Avoid a hundred -Wflex-array...”)

```
struct wl1251_cmd_header {
    u16 id;
    u16 status;
-   /* payload */
-   u8 data[];
 } __packed;
```

-Wflex-array-member-not-at-end

Case 2: **FAMs never accessed through the composite struct**.

-Wflex-array-member-not-at-end

Case 2: **FAMs never accessed through the composite struct**.

```
struct flex {
    int a;
    int b;
    size_t  count;
    struct foo fam[];
};

struct composite {
    ...
    struct flex middle; /* -Wfamnae warning */
    ...
} *p;
...


do_something_with(p->middle.a, p->middle.b);
```

-Wflex-array-member-not-at-end

Case 2: **FAMs never accessed through the composite struct**.

```
struct flex {
    int a;
    int b;
    size_t  count;
    struct foo fam[];
};

struct composite {
    ...
    struct flex middle; /* -Wfamnae warning */
    ...
} *p;
...

/* We may access the rest of the members in struct flex */
do_something_with(p->middle.a, p->middle.b);
```

-Wflex-array-member-not-at-end

Case 2: **FAMs never accessed through the composite struct**.

– What can we do about it?

```
struct flex {
    int a; int b;
    size_t count;
    struct foo fam[];
};

struct composite {
    ...
    struct flex middle; /* -Wfamnae warning */
    ...
};
```

-Wflex-array-member-not-at-end

Case 2: **FAMs never accessed through the composite struct**.

```
struct flex { /* original struct */
    int a; int b;
    size_t count;
    struct foo fam[] __counted_by(count);
};

struct flex_hdr {
    int a; int b;
    size_t count;
};
```

-Wflex-array-member-not-at-end

- Case 2: **FAMs never accessed through the composite struct**.
  - Two separate structs: original struct & header struct

```
struct flex { /* original struct */
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    size_t count;
    struct foo fam[] __counted_by(count);
};

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    int a; int b;
    size_t count;
};
```

-Wflex-array-member-not-at-end

Case 2: **FAMs never accessed through the composite struct**.

- Two separate structs: original struct & header struct
- New header struct named after original flex struct.

```
struct flex { /* original struct */
    int a; int b;
    size_t count;
    struct foo fam[] __counted_by(count);
};

struct flex_hdr {
    int a; int b;
    size_t count;
};
```

-Wflex-array-member-not-at-end

Case 2: **FAMs never accessed through the composite struct**.

- Two separate structs: original struct & header struct
- New header struct named after original flex struct.

```
struct flex { /* original struct */
    int a; int b;
    size_t count;
    struct foo fam[] __counted_by(count);
};

struct flex_hdr { /* All members in struct flex except the FAM */
    int a; int b;
    size_t count;
};
```

-Wflex-array-member-not-at-end

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- New header struct named after original flex struct.

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struct flex_hdr { /* All members in struct flex except the FAM */
    int a; int b;
    size_t count;
};
```

-Wflex-array-member-not-at-end

Case 2: **FAMs never accessed through the composite struct**.

- Two separate structs: original struct & header struct

```
struct composite { /* BEFORE */
    ...
    struct flex middle; /* -Wfamnae warning :( */
    ...
};

struct composite { /* AFTER */
    ...
    struct flex_hdr middle;
    ...
};
```

-Wflex-array-member-not-at-end

- Case 2: **FAMs never accessed through the composite struct**.
  - Two separate structs: original struct & header struct

```
struct composite { /* BEFORE */
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    ...
};

struct composite { /* AFTER */
    ...
    struct flex_hdr middle;
    ...
};
```

-Wflex-array-member-not-at-end

- Case 2: **FAMs never accessed through the composite struct**.
  - Two separate structs: original struct & header struct

```
struct composite { /* BEFORE */
    ...
    struct flex middle; /* -Wfamnae warning :( */
    ...
};

struct composite { /* AFTER */
    ...
    struct flex_hdr middle; /* Life's beautiful! ^.^ */
    ...
};
```

-Wflex-array-member-not-at-end

Case 2: **FAMs never accessed through the composite struct**.

– What’s the problem with this?

```
struct flex { /* original struct */
    int a; int b;
    size_t count;
    struct foo fam[] __counted_by(count);
};

struct flex_hdr { /* All members in struct flex except the FAM */
    int a; int b;
    size_t count;
};
```

-Wflex-array-member-not-at-end

- Case 2: **FAMs never accessed through the composite struct**.
  - Duplicate code.

```
struct flex { /* original struct */
    int a; int b;
    size_t count;
    struct foo fam[] __counted_by(count);
};

struct flex_hdr { /* All members in struct flex except the FAM */
    int a; int b;
    size_t count;
};
```

-Wflex-array-member-not-at-end

Case 2: **FAMs never accessed through the composite struct**.

- Duplicate code.

```
struct flex { /* original struct */
    int a; int b;
    size_t count;
    struct foo fam[] __counted_by(count);
};

struct flex_hdr { /* All members in struct flex except the FAM */
    int a; int b;
    size_t count;
};
```

-Wflex-array-member-not-at-end

Case 2: **FAMs never accessed through the composite struct**.

- Duplicate code.
- Maintain two independent but basically identical structs.

```
struct flex { /* original struct */
    int a; int b;
    size_t count;
    struct foo fam[] __counted_by(count);
};

struct flex_hdr { /* All members in struct flex except the FAM */
    int a; int b;
    size_t count;
};
```

-Wflex-array-member-not-at-end

- Case 2: **FAMs never accessed through the composite struct**.
  - Use struct_group_tagged()/__struct_group()

-Wflex-array-member-not-at-end

Case 2: **FAMs never accessed through the composite struct**.

- Use struct_group_tagged()/__struct_group()

```
struct flex { /* BEFORE */


    int a; int b;
    size_t  count;

    struct foo fam[] __counted_by(count);
};

struct composite { /* BEFORE */
    ...
    struct flex middle; /* -Wfamnae warning */
    ...
} *p;
```

-Wflex-array-member-not-at-end

Case 2: **FAMs never accessed through the composite struct**.

- Use struct_group_tagged()/__struct_group()

```
struct flex { /* AFTER */
    /* New members must be added within the struct_group() macro below. */
    struct_group_tagged(flex_hdr, hdr,
        int a; int b;
        size_t count;
    );
    struct foo fam[] __counted_by(count);
};

struct composite { /* BEFORE */
    ...
    struct flex middle; /* -Wfamnae warning */
    ...
} *p;
```

-Wflex-array-member-not-at-end

Case 2: **FAMs never accessed through the composite struct**.

– Use struct_group_tagged()/__struct_group()

```
struct flex { /* AFTER */
    /* New members must be added within the struct_group() macro below. */
    struct_group_tagged(flex_hdr, hdr,
        int a; int b;
        size_t  count;
    );
    struct foo fam[] __counted_by(count);
};

struct composite { /* AFTER */
    ...
    struct flex_hdr middle; /* FAM is gone! ^.^ */
    ...
} *p;
```

The **struct_group()** family of helpers

Created by Kees Cook and Keith Packard

```
#define struct_group_tagged(TAG, NAME, MEMBERS...) \
        union {                                    \
                struct { MEMBERS };                \
                struct TAG { MEMBERS } NAME;       \
        }
```

The **struct_group()** family of helpers

- Created by Kees Cook and Keith Packard
  - Access each member directly or via the named struct.

```
#define struct_group_tagged(TAG, NAME, MEMBERS...) \
        union {                                    \
                struct { MEMBERS };                \
                struct TAG { MEMBERS } NAME;       \
        }
```

The **struct_group()** family of helpers

- Created by Kees Cook and Keith Packard
  - Access each member directly or via the named struct.
  - Create a new struct type and define an identifier for the group

```
#define struct_group_tagged(TAG, NAME, MEMBERS...) \
        union {                                     \
                struct { MEMBERS };                 \
                struct TAG { MEMBERS } NAME;        \
        }
```

The **struct_group()** family of helpers

Created by Kees Cook and Keith Packard

- Access each member directly or via the named struct.
- Create a new struct type and define an identifier for the group – via which we can gain bounds-checking.

```
#define struct_group_tagged(TAG, NAME, MEMBERS...) \
        union {                                    \
                struct { MEMBERS };                \
                struct TAG { MEMBERS } NAME;       \
        }
```

-Wflex-array-member-not-at-end

Case 2: **FAMs never accessed through the composite struct**.

– Use struct_group_tagged()/__struct_group()

```
struct flex { /* AFTER */
    /* New members must be added within the struct_group() macro below. */
    struct_group_tagged(flex_hdr, hdr,
        int a; int b;
        size_t  count;
    );
    struct foo fam[] __counted_by(count);
};

struct composite { /* AFTER */
    ...
    struct flex_hdr middle; /* FAM is gone! ^.^ */
    ...
} *p;
```

```
p->middle.a
p->middle.b
p->middle.count

p->middle.hdr.a
p->middle.hdr.b
p->middle.hdr.count
```

-Wflex-array-member-not-at-end

Case 2: **FAMs never accessed through the composite struct**.

– 5c4250092fad (“wifi: mwl8k: Avoid -Wflex-array-…”)

```
 struct mwl8k_cmd_pkt {
-	__le16	code;
-	__le16	length;
-	__u8	seq_num;
-	__u8	macid;
-	__le16	result;
+	__struct_group(mwl8k_cmd_pkt_hdr, hdr, __packed,
+		__le16	code;
+		__le16	length;
+		__u8	seq_num;
+		__u8	macid;
+		__le16	result;
+	);
	char payload[];
 } __packed;
```

-Wflex-array-member-not-at-end

- Case 2: **FAMs never accessed through the composite struct**.
  - 5c4250092fad (“wifi: mwl8k: Avoid -Wflex-array-…”)

```
 struct mwl8k_cmd_pkt {
-    __le16  code;
-    __le16  length;
-    __u8    seq_num;
-    __u8    macid;
-    __le16  result;
+    __struct_group(mwl8k_cmd_pkt_hdr, hdr, __packed,
+        __le16  code;
+        __le16  length;
+        __u8    seq_num;
+        __u8    macid;
+        __le16  result;
+    );
     char payload[];
 } __packed;
```

-Wflex-array-member-not-at-end

- 5c4250092fad (“wifi: mwl8k: Avoid -Wflex-array-…”)
- Replace *mwl8k_cmd_pkt* with *mwl8k_cmd_pkt_hdr*

```
 struct mwl8k_cmd_rf_antenna {
-	struct mwl8k_cmd_pkt header;
+	struct mwl8k_cmd_pkt_hdr header;
 	__le16 antenna;
 	__le16 mode;
 } __packed;
```

-Wflex-array-member-not-at-end

- 5c4250092fad (“wifi: mwl8k: Avoid -Wflex-array-…”)
- Replace *mwl8k_cmd_pkt* with *mwl8k_cmd_pkt_hdr*

```
  struct mwl8k_cmd_rf_antenna {
-	struct mwl8k_cmd_pkt header;
+	struct mwl8k_cmd_pkt_hdr header;
 	__le16 antenna;
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-Wflex-array-member-not-at-end

Case 3: **Implicit unions** between FAMs and fixed-size arrays of the same element type.

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```
struct flex_struct {
    ...
    size_t  count;
    struct foo flex_array[] __counted_by(count);
};

struct composite_struct {
    ...

    struct flex_struct flex_in_the_middle;
    struct foo fixed_array[MAX_LENGTH];
    ...
} __packed;
```

-Wflex-array-member-not-at-end

Case 3: **Implicit unions** between FAMs and fixed-size arrays of the same element type.

```
struct flex_struct {
    ...
    size_t  count;
    struct foo flex_array[] __counted_by(count);
};

struct composite_struct {
    ...

    struct flex_struct flex_in_the_middle;
    struct foo fixed_array[MAX_LENGTH];
    ...
} __packed;
```

-Wflex-array-member-not-at-end

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```
struct flex_struct {
    ...
    size_t  count;
    struct foo flex_array[] __counted_by(count);
};

struct composite_struct {
    ...

    struct flex_struct flex_in_the_middle;
    struct foo fixed_array[MAX_LENGTH];
    ...
} __packed;
```

- flex_array and fixed_array share the same address in memory - in the best scenario.
- Both form an implicit union.

-Wflex-array-member-not-at-end

Case 3: **Implicit unions** between FAMs and fixed-size arrays of the same element type.

```
 struct ima_digest_data { /* flexible struct */
+   /* New members must be added within the __struct_group() macro below. */
+   __struct_group(ima_digest_data_hdr, hdr, __packed,
        u8 algo;
        u8 length;
        ...
+   );
    u8 digest[];
 } __packed;
```

```
/* implicit union: FAM & fixed-size array*/
 struct ima_max_digest_data {
-  struct ima_digest_data hdr;
+  struct ima_digest_data_hdr hdr;
   u8 digest[HASH_MAX_DIGESTSIZE];
 } __packed;
```

-Wflex-array-member-not-at-end

Case 3: **Implicit unions** between FAMs and fixed-size arrays of the same element type.

```
 struct ima_digest_data { /* flexible struct */
+   /* New members must be added within the __struct_group() macro below. */
+   __struct_group(ima_digest_data_hdr, hdr, __packed,
        u8 algo;
        u8 length;
        ...
+   );
    u8 digest[];
 } __packed;
```

```
/* implicit union: FAM & fixed-size array*/
 struct ima_max_digest_data {
-  struct ima_digest_data hdr;
+  struct ima_digest_data_hdr hdr;
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-Wflex-array-member-not-at-end

Case 3: **Implicit unions** between FAMs and fixed-size arrays of the same element type.

– However, **FAM digest** is accessed at run-time.

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  struct ima_max_digest_data hash;
  ...
  /* read data from the FAM digest */
  memcpy(digest_hash, hash.hdr.digest, digest_hash_len);
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- Access FAM through that pointer.

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    struct ima_max_digest_data hash; /* struct with implicit union */
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- Use **container_of()** to get a pointer to the flex struct.
- Access FAM through that pointer.
- 38aa3f5ac6d2 (“integrity: Avoid -Wflex-array-member...”)

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    struct ima_max_digest_data hash; /* struct with implicit union */
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... hash_hdr is now a pointer to flex struct ima_digest_data

        /* read data from the FAM digest */
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Case 4: **Implicit unions** between FAMs and fixed-size arrays of the same element type – **on stack**.

-Wflex-array-member-not-at-end

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```
struct flex_struct {
    ...
    size_t  count;
    struct foo flex_array[] __counted_by(count);
};


int some_function(...) /* on-stack -Wfamnae warning */
{
    struct {
        struct flex_struct flex;
        struct foo fixed_array[10];
    } obj = ...
    ...
}
```

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```c
struct fun_admin_bind_req {
    struct fun_admin_req_common common;
    struct fun_admin_bind_entry entry[];
};

int fun_bind(...) /* on-stack -Wfamnae warning */
{
    struct {
        struct fun_admin_bind_req req;
        struct fun_admin_bind_entry entry[2];
    } cmd = ...
    ...
}
```

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```
struct fun_admin_bind_req {
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    struct fun_admin_bind_entry entry[];      /* flex-array member */
};

int fun_bind(...) /* on-stack -Wfamnae warning */
{
    struct {
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    } cmd = ...
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Case 4: **Implicit unions** between FAMs and fixed-size arrays of the same element type – **on stack**.

- We use **DECLARE_FLEX()** and **DECLARE_RAW_FLEX()** helpers.
- Some examples:
  - 6c85a13b133f (“platform/chrome: cros_ec_proto:…”)
  - 4d69c58ef2e4 (“fsnotify: Avoid -Wflex-array-mem…”)
  - 215c4704208b (“Bluetooth: L2CAP: Avoid -Wflex-...”)

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A simple three-step solution for the complex case:

- Use **struct_group_tagged()** to create a new tagged struct.
  - This groups together all members in the flex struct **except the FAM**.
- **Change the type** of the conflicting object to the newly created tagged struct.
- Use **container_of()** to retrieve a pointer to the flex struct when needed.
  - Access the **FAM** via this pointer if necessary.

Conclusions

For implicit unions on the stack:

- Use **DECLARE_FLEX()** when the FAM is annotated with __counted_by().
- We can use **DECLARE_RAW_FLEX()** in any other case.

Conclusions

- Clear strategy to enable **-Wflex-array-member-not-at-end** in mainline, soon.
- A couple (three) dozen patches are already in mainline.
- Down to ~300 (from ~650) unique warnings.
- ~30% of total warnings addressed so far.

Thank you, Paris!

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By @shidokou