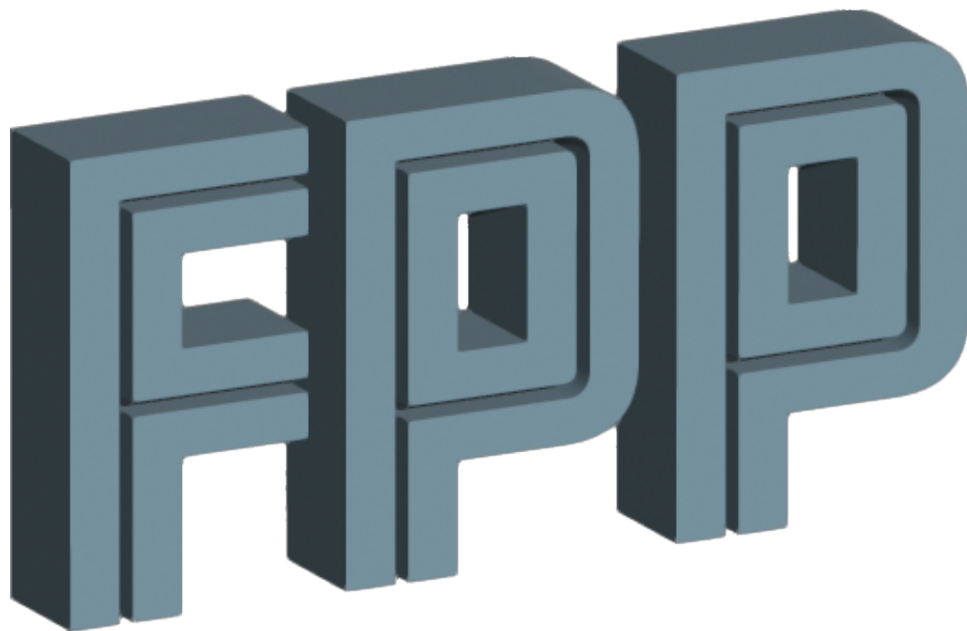

Fully Polymorphic Package Manual



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1 Introduction to packages within FPP/PTC

The name PTC is commonly used to designate a code written by Etienne Forest with the help of Frank Schmidt and later David Sagan. PTC is an object oriented, open source, subroutine library for

- The manipulation and analysis of Taylor series and Taylor maps.
- Modeling of charged particle beams in accelerators using Taylor maps.

The popularity of PTC can be attested to by its use with the Bmad[b:bmadv] toolkit for accelerator and X-ray simulations as well as its use within the MAD[b:mad] simulation program.

PTC is linked with the overloaded Truncated Power Series Algebra (TPSA) package of Martin Berz. Berz's package is called **Polymorphic Package** (PP). By virtue of using the polymorphic package and by virtue of being able to do tracking, PTC stands for "Polymorphic Tracking Code". PTC can be decomposed into two parts:

1. The Fully Polymorphic Package (FPP) part handles Taylor series. FPP is pure mathematics detached from any "physics".
2. The Tracking Code (TC) part is where the physics of PTC is located. It is simply an integrator pushing the phase space and spin of particles through magnets. TC relies on FPP for handling Taylor series. In particular, via the magic of FPP (specifically the magic of PP), a Taylor map can be produced if wanted when tracking with TC.

FPP is the subject of this manual. FPP itself can be subdivided into two parts:

1. The "Polymorphic Package" (the PP of FPP) deals with the production of Taylor series.
2. The Analysis Package (AP) analyses physically sensible Taylor maps: Taylor maps that approximate the tracking of the code. Spin and magnet modulation can also be analyzed.

To appreciate the role of PP, we can show a tiny piece of code TC representing a drift.

```
      .  
      .  
      .  
      TYPE(REAL_8), INTENT(INOUT):: X(6)  
      TYPE(REAL_8), INTENT(IN):: L  
      .  
      .  
      .  
      PZ=SQRT(1.0_dp+2.0_dp*X(5)/b+x(5)**2-X(2)**2-X(4)**2)  
      X(1)=X(1)+L*X(2)/PZ  
      X(3)=X(3)+L*X(4)/PZ
```

If type **REAL_8** was simply **real(8)**, then this code fragment would simply be the exact formula for a drift in canonical variables. However **REAL_8** can become a Taylor series in certain chosen

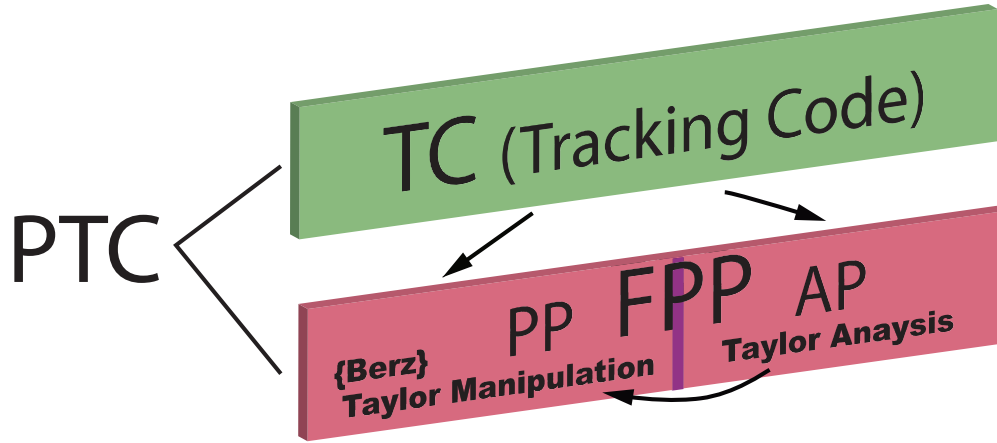


Figure 1: The Fully Polymorphic Package (FPP) part of the FPP/PTC library provides manipulation and analysis of Taylor series and maps and the Tracking Code (TC) part contains the physics of the accelerators. Arrows indicate code dependencies. The Taylor analysis code uses the Taylor manipulation code but not vice versa. FPP does not use PTC but PTC code uses both FPP's Taylor manipulation and potentially analysis as the red arrow indicates.

variables at execution time and thus Taylor series can be produced. The actual package that does the Taylor calculation is the package of Martin Berz[b:berz.da] , namely the old version from LBNL properly modified by Johan Bengtson and overloaded by Etienne Forest using Fortran90.

This manual is focused on how to use FPP. Since FPP is designed to serve PTC or a code like PTC, there will be some mention of PTC but only so far as how PTC relates to FPP. In particular, tracking through lattices is not discussed and the reader is referred to the PTC documentation for this.

The red arrow in Figure 1 refers to a potential dependency. PTC can dump on files Taylor series which can be analyzed or tracked by another code. Conversely, PTC (via FPP), can read maps produced by other codes and track them. For example, a person might have a COSY-INFINITY version of a damping ring and the subsequent injection line. The Taylor map describing this structure can be an input to PTC in the absence of a PTC lattice for this structure: this is equivalent to inputting linear uncoupled lattice functions in a regular code but much more general.

In fact most analysis in PTC is done by people (including the authors) who write independent modules for generalized Twiss calculations. This will be illustrated later and is the main topic of reference [thenewbook].

The FPP package can be used with any tracking code including TC. Indeed one can write an integrator in Fortran90 using the polymorphic types of FPP for the production and analysis of Taylor maps: Forest has written many such examples in lectures.

2 Where to Obtain FPP/PTC

FPP/PTC can be downloaded from the web via the Bmad web site**[b:Bmad]** or at

```
https://github.com/jceepf/fpp_book
```

Taylor manipulation routines are contained in the following code files:

```
a_scratch_size.f90      j_tpsalie.f90
b_da_arrays_all.f90     k_tpsalie_analysis.f90
b_da_arrays_all_pancake.f90 l_complex_taylor.f90
c_dabnew.f90            m_real_polymorph.f90
c_dabnew_pancake.f90    n_complex_polymorph.f90
d_lielib.f90            o_tree_element.f90
h_definition.f90        Sa_extend_poly.f90
i_tpsa.f90
```

Taylor analysis routines are contained in the following code files

```
cb_da_arrays_all.f90    Ci_tpsa.f90
cc_dabnew.f90           Su_duan_zhe_map.f90
```

The library

```
Su_duan_zhe_map.f90
```

can actually be used separately. It allows for tracking using Taylor maps: remember that PTC proper (TC) does not use Taylor maps for tracking, it is a “kick code” or integrator.

3 Concepts: Taylor series, polymorphs and Taylor maps

The purpose of this section is to explain why we would like to write an integrator equipped with polymorphism. Of course the purpose exists before the code and, for the most part, is not the result of “Darwinian evolution”.

It is true from a goal driven point of view (teleological) that PTC was created with the production of Taylor maps of phase space in mind. This is simply because Forest is convinced, see references **[thebook]** and **[thenewbook]**, that an analytical theory primarily based on finite “s” maps is superior than a theory primarily based on the s-dependent Hamiltonian of the Courant-Snyder theory. This s-dependent Hamiltonian is far from the code and thus not adequate as the primary theory for most applications.

But can we guess from TC’s structure, the tracking part, that PTC prioritizes a map-based theory for analysis? The answer as we will see is :no.

There are two options if we have Taylor maps in mind:

1. We can write a beam line code whose goal is the production of Taylor series approximate maps around some chosen orbit and whose internal structure reflects this goal. The prime representative of such codes is COSY-INFINITY[**cosy9**, **cosynim**]. This is also true of

MARYLIE, TRANSPORT[slac75] and the Twiss modules part of MAD8 ported into MAD-X. All these codes choose a “design” orbit and then compute Taylor maps around this orbit. If a user examine these codes, especially TRANSPORT, Taylor series maps will jump in their faces: arrays of monomial coefficients for each phase space variables are defined and they contain increasingly complex formulae as the degree increases. The TRANSPORT approach reached a grotesque end point with the code COSY 5.0¹ of Berz : Fortran formulae at the fifth order Taylor coefficients covered pages of computer generated algebra.

2. Forest, following mainly the philosophy of Talman, prefers the usage of integrators, in particular, symplectic integrator in the simulations of LINACs, recirculators and rings. (See Forest’s review article [forestreview] for a comprehensive opinionated description of this topic.) As a result, and irrespective of teleological consideration i.e., wanting Taylor maps for analysis–Twiss, etc..., TC is a (mostly symplectic) integrator whose main purpose is the tracking of rays. It is only via polymorphism that this integrator can, under some very specific conditions, produce a Taylor map which approximates the phase space maps produced by the likes of COSY-INFINITY or MARYLIE.

In fact Forest produced a “kick code”. Imagine if the type **real_8** was a Fortran90 intrinsic. Anyone could write a kick code using the floating point **real(8)**. The fact that same person could recompile the code using **real_8** would not automatically elevate the code to a code which produces sensible phase space maps. COSY-INFINITY, MARYLIE or TRANSPORT on the other hand always produce sensible maps when applied to magnets: this is their end purpose and their internal structure can be guessed from their purpose.

Looking internally at TC, it is not possible to see any maps²: only tracking of **real_8** completely mimicking the tracking of **real(8)**.

Therefore it is not mathematically true that PTC produces “Taylor maps” despite Forest’s motives. Sometimes PTC produces Taylor series and it is not clear to the author of PTC (Forest) what kind of maps should be created. An example of this is provided in sections (§5.2) and (§5.3): from the Taylors series produced by PTC we construct a contracting map to be used in a Newton search. In that case, the user must write the interface since no one can guess *a priori* what the user has in mind.

We will see that PTC provides an interface between TC and AP which privileges the production of phase space maps so that the users can *de facto* state that for the most part PTC facilitates the production of Taylor maps related to phase space via the derived type **real_8**. But this is not visible in TC proper and is only true because Forest has programmed a very specific interface between polymorphs and Taylor maps. He could have left that task to the user (Bmad and MAD-X programmers) but they would have complained. Forest himself as the prime user would have complained schizophrenically to himself.

In the rest of this section we explain TC’s interaction with FPP. It is thus necessary to introduce certain concepts in very broad terms. Since PTC is an existing code, we can use its existing

¹This is not to be confuse with COSY-INFINITY which uses Berz’s TPSA package. COSY 5.0[cosy5ham] was really the end of the dinosaur line of TRANSPORT like codes. It is mercifully extinct.

²A now retired CERN scientist exclaimed upon looking in the guts of PTC: “where are the beta functions?” The reader should understand upon reading this manual that this question is ridiculous: they are nowhere. PTC is unaware of them even when it tracks them! This is the central topic of reference [thenewbook].

structures to describe the general approach. Someone else, writing in a different language would most likely be tempted to use similar concepts and perhaps do a better job.

After general considerations to set the tone and provide some context, we will examine 3 cases in section (§3.5):

1. In section (§5.1), we extract a phase space map. We use special constructs and routines that facilitates this for the user. Namely they connect TC to AP. In AP, normal forms for example have very special assumptions : they deal with linearly stable spin-orbit maps for example.
2. In sections (§5.2) and (§5.3), we create a contraction map that fits the output of TC that has no connection with accelerator theory proper. FPP is used directly without the interface to AP. This program can be understood without the slightest understanding of TC and what it allegedly computes.
3. In section (§5.4), we fit the orbit (as in item 2) and the tunes/phase-slip. This is a typical accelerator physics case. We create the usual one-turn maps as well as the Langrangian contraction maps of item 2.

3.1 Conventions

FPP/PTC is written in Fortran90. It is assumed that the reader has some familiarity with this language. In particular, it is assumed that the reader knows what a **structure** is (roughly corresponding to a **class** in Python or C++) which is also called a **derived type**. Additionally it is assumed that the reader knows about operator overloading.

FPP/PTC uses double precision numbers. The kind type parameter “**dp**” is defined in FPP/PTC to correspond to double precision numbers. For example:

```
real(dp) abc, xyz      ! Declare double precision vars abc and xyz.
xyz = 3.4_dp * abc / 1e9_dp ! 3.4_dp and 1e9_dp are double precision.
```

In this manual, **real(dp)** is often written as **real(8)** in case the meaning of **dp** is forgotten. However **dp** could be **16** if quadruple precision is used.

3.2 TPSA Versus DA

TPSA stands for “Truncated Power Series Algebra” and DA stands for “Differential Algebra.” What does it mean when applied to a typical accelerator ring? Once we cut the mathematical jargon, we will see that

- TPSA operations take into account the constant part and the results change as a function of the order (see below).
- DA operations are equivalent to normal TPSA operations used around the closed orbit and thus the constant part of the map is ignored. All the coefficients of the Taylor series stay the

same independently of the order invoked. It so happens that the computation of nonlinear differential operators (Lie vector fields for example), are self-consistent because they form a differential algebra. But it is much simpler in our field to state that they are self-consistent because there are no feed down terms.

It is important to understand why a non-zero constant part of a Taylor series can be problematical. To see this, consider two TPSA maps of order N . One maps x to y and the second maps y to z :

$$y = \sum_{j=0}^N a_j x^j \quad (1)$$

$$z = \sum_{j=0}^N b_j y^j + \mathcal{O}(y^{N+1}) \quad (2)$$

In Eq. (2) it is made explicit that there are terms of order $N + 1$ or higher that are being neglected. The two maps can be concatenated to form a map of w as a function of x :

$$w(x) = \sum_{j=0}^N c_j x^j \equiv z(y(x)) \quad (3)$$

If there is a neglected term in Eq. (2) that looks, for example, like $b_m y^m$ with $m > N$, substituting Eq. (1) into this term will result in modification of all lower order terms in Eq. (3) if, and only if, a_0 is non-zero. This is called “feed-down”. That is, terms of higher order will affect the coefficients of lower order terms when TPSA maps are combined. To avoid this, maps with zero constant term (DA maps) should be used. With simulations, this generally means computing maps with respect to the orbit. For lattices with a closed geometry, this generally means computing maps with respect to the **actual period-one closed** orbit. For lattices with an open geometry (EG: Linacs), the reference orbit can be some orbit defined by tracking a beam from some **wisely** user-specified initial position.

3.3 Polymorphism

In computer programming “**polymorphism**” is the property that a given variable, object, or function can act in different ways depending upon the context. With FPP/PTC, polymorphism is used to define types that can act as if the structure components were real valued numbers or Taylor series. See the documentation of the **real_8** type (§8) as an example.

Note: Many **PTC** tracking code routines come in pairs. One routine of the pair, typically having a “r” suffix in its name, will use real variables while the other routine, typically having a “p” suffix in its name. **One could track real numbers with the polymorphic routines but this with entail a substantial speed decrease and therefore we opted for a duplication of the routines.**

Polymorphic types always have structure names that have a **_8** suffix.

3.4 Operator Overloading

FPP/PTC heavily uses operator overloading for the manipulation of Taylor series and polymorphs. Not only are the standard arithmetical operators (+, -, *, /, **) overloaded as well as the equal sign (=), but there are a number of custom operators that are defined as well. Below is a partial list.³

+, -

Standard addition and subtraction of Taylor series.

*M1 * M2* is used with two maps for a DA concatenation while *M1.o.M2* is a TPSA concatenation with constant part retained.

.o.

Powers of Taylor maps

.oo.

Powers of Taylor maps using .o. for concatenation.

The difference between .o. and * was explained in section (S4) using a one-dimensional example for simplicity.

3.5 Tracking Versus Analysis

An important distinction here is the difference between **tracking** and **analysis**. By “tracking” it is meant the propagation through a lattice of a single particle which typically involves six **real_8** numbers for the orbital motion and four **real_8** for spin represented via a quaternion.

However, with objects ending in **_8**, the orbital part and the quaternion can internally become Taylor series in some variables via polymorphism. *De facto*, if these polymorphs are properly initialized, then we can end up tracking Taylor series which can be turned into *bona fide* Taylor maps which approximate the beam line as they do in COSY-INFINITY or MARYLIE. Typically this is used to either compute a one-turn Taylor map or propagate a canonical transformation such as the Courant-Snyder transformation. However it could also produce a map unrelated to the usual one-turn map, for example, the closed orbit as a Taylor series in dipole strengths or anything ...⁴ This is opposed to “analysis” which is the study of a Taylor transport map to extract such things as tunes, lattice functions, resonance driving terms, etc. With FPP, analysis is always done on Taylor maps.

³Note: Fortran mandates that custom operator names begin and end with a dot “.”. These operators have the lowest priority and therefore require parentheses. The usual Fortran operators, if overloaded, inherit the priorities of the intrinsic operators.

⁴Mathematically, single particle tracking is just tracking using Taylor series truncated at zeroth order. From the code perspective, due to the speed reduction with dealing with Taylor series, the two are distinct: the routines with suffixes **_r** and **_p**.

3.6 TC tracks elements of the algebra ${}_{no}D_{nv}$

The purpose of this section is to unpack clearly the statement that PTC can track Taylor maps while TC tracks polymorphs which are members of an algebraic extensions of the real numbers. We do this with examples because in the end, all of this is very trivial if we focus on applications rather than theory. For the theory, the reader can look at Berz's book [**theberzbook**] and in particular the section on Levi-Civita fields⁵ which provide inverses to the infinitesimals.

Since any function is a map, we usually reserve the word map to a function of phase space which, in TC, is of dimension 2 at a minimum. Therefore when PTC invokes TPSA it will always track Taylor "maps" but they can be nonsensical as a beam line map. We do allow PTC to track without any TPSA monomials reserved for the orbital motion, but this is only permitted if the TPSA package is initialized with a subroutine proper to FPP: it forces the programmer to view TC as just an "unknown" black box subroutine. We will see what it implies in section (§5.2).

Mathematically what does TC track?

A normal "kick" code tracks a subset of the field $(\mathbb{R}, +, \times)$, namely floating point numbers. When embedded in the code Bmad, the TC subroutine "**propagate**", which we will encounter in the examples, is a function (or map in the usual mathematical sense) from :

$$\mathbb{R}^6 \xrightarrow{TC} \mathbb{R}^6 \quad (4)$$

$$z \longrightarrow z^f = TC(z) \quad (5)$$

$$\text{where in BMAD } z = (x, P_x/p_0, y, P_y/p_0, \beta_{ct}, \delta P/p_0) \in \mathbb{R}^6 \quad (6)$$

PTC or **propagate** is a map of \mathbb{R}^6 in PTC at a minimum. (Spin and other goodies can be included).

Polymorphism extends $(\mathbb{R}, +, \times)$ to an algebra called by Berz[**theberzbook**] ${}_{no}D_{nv}$, i.e., to $({}_{no}D_{nv}, +, \times)$. This is the TPSA algebra described in §3.2. This algebra is a ring, not a field, i.e., not all elements have inverses. In fact all the so-called infinitesimals have no inverses. Colloquially, we might say that we deal with Taylor series not Laurent series. Thus we can say very clearly that

$${}_{no}D_{nv}^6 \xrightarrow{TC} {}_{no}D_{nv}^6 \quad (7)$$

$$z \longrightarrow z^f = TC(z) \quad (8)$$

$$\text{where } z = (x, p_x/p_0, y, p_y/p_0, \beta_{ct}, \delta p/p_0) \in {}_{no}D_{nv}^6 \quad (9)$$

As an example, we can use a 1-d example as in Eq. (37). Consider two second order polynomials in one-variable, i.e., elements of ${}_2D_1$:

$$\begin{aligned} \text{if } m &= m_0 + m_1\Delta + m_2\Delta^2 \\ \text{and } n &= n_0 + n_1\Delta + n_2\Delta^2 \end{aligned} \quad (10)$$

then we can write

$$\begin{aligned} \text{if } m &\equiv (m_0, m_1, m_2) \in {}_2D_1 \\ \text{and } n &\equiv (n_0, n_1, n_2) \in {}_2D_1 \end{aligned} \quad (11)$$

⁵We think that it is better for most readers to get a practical view of Berz's idea before reading his exposition of such fields.

In Eq. (11), we use the array notation for elements of the ring ${}_2D_1$ which is more in line with the actual Fortran90 code. Then we have:

$$m \pm n = (m_0 \pm n_0, m_1 \pm n_1, m_2 \pm n_2) \quad (12)$$

and for multiplication,

$$m \times n = (m_0 n_0, m_0 n_1 + m_1 n_0, m_2 n_0 + m_1 n_1 + m_0 n_2) \quad (13)$$

and finally for division we have,

$$m \div n = \left(\frac{m_0}{n_0}, -\frac{m_0 n_1 - m_1 n_0}{n_0^2}, -\frac{m_0 n_0 n_2 - m_0 n_1^2 + m_1 n_0 n_1 - m_2 n_0^2}{n_0^3} \right) \quad (14)$$

It should be clear from this example that we regain the field of real (or complex) numbers if only the entry of the element of ${}_2D_1$ is used. Secondly, if $n_0 = 0$, then the division of Eq. (14) is not defined: we have a ring, not a scalar field (See Berz[theberzbook]).

When TC tracks elements of ${}_nD_{nv}$, it is totally “unaware” that these objects can be turned into *bona fide* phase space Taylor maps: this was shown in the drift code fragment of section (§1) where no “Taylor maps” are to be seen. In order to explain this dichotomy between tracking and analysis, between polymorphs and Taylors maps, we need to define different structures of FPP/PTC that are optimized to handle one or the other. Structures that have been designed to handle tracking are

```
TC structures

real_8
complex_8      (only used internally in TC)
probe_8
probe          (this is the real version of probe_8)
```

and for analysis here is an important subset

```
AP structures

c_taylor
c_damap
c_normal_form
c_vector_field
```

Finally we have structures which allow us to save Taylor series outside the TPSA package(s) of Berz. This is a permanent kind of storage that does not depend on the order and number of variables used by the TPSA of Berz which underpins FPP. They are totally independent.

```
Storage structures

universal_taylor
c_universal_taylor
```

While the structures that PTC uses for tracking are discussed here, the details of how to track through a lattice are deferred to the PTC documentation. Here the primary concern is FPP and analysis as well as the interaction between analysis and tracking, between AP and TC.

The interaction between the world of polymorphs **_8**, which are elements of ${}_{no}D_{nv}$ and Taylor maps, we will illustrate below in section (§5.1). In summary, the code TC produces the usual orbital and spin but, via polymorphism, it can be fed into a structure **c_damap**, which is a Taylor map and thus can be analyzed if sensible. The result of this analysis, for example a Courant-Snyder transformation, in the form of a **c_damap**, can then be fed into a polymorphic ray (**probe_8**, and tracked again. This is how one does any type of Twiss calculation, i.e., propagates canonical transformations including spin and nonlinearities. This is the topic of reference [thenewbook].

Nota Bene:

In summary, there are 3 ways to look at a TPSA variable. They are all isomorphic mathematically but they serve very different purposes in the human brain.

1. As a polynomial in some variable, say Δ of Eq. (10), with automatic truncation at order $no + 1$. Our brains are in physics mode when doing this.
2. As a polynomial in some abstract object, say Δ of Eq. (10), where $\Delta^{no+1} = 0$. In that case we are dealing with an abstract representation of ${}_{no}D_{nv}$. This is useful when thinking about $({}_{no}D_{nv}, +, \times)$. Our brains are in mathematical mode.
3. Finally, the algebra $({}_{no}D_{nv}, +, \times)$ can be represented as an n-tuple as in Eq. (11). Here we are in a computer science mode since ultimately the computer stores all the TPSA variables in arrays with specific rules under addition and multiplication.

Item 3 is fully demonstrated if one downloads from the git site the following folder:

https://github.com/jceepf/fpp_book/my_demo_package

This folder contains a mini-TPSA and analysis package as well as a nonlinear Twiss example.

Indeed, the TSPA package of that site (no polymorph but only Taylor) contains the following definition of a Taylor derived type:

```
TYPE my_taylor
  complex(dp) a(0:n_mono)
END TYPE my_taylor
```

This package can represent $({}_0D_3, +, \times)$, $({}_1D_3, +, \times)$, $({}_2D_3, +, \times)$, $({}_3D_3, +, \times)$ and $({}_4D_3, +, \times)$. Obviously $({}_0D_3, +, \times)$ is just the field of complex numbers $(\mathbb{C}, +, \times)$ where each number is stored **my_taylor%a(0)**.

Moreover addition and subtraction are defined respectively by overloading the Fortran90 intrinsic operators via the following functions:

```
FUNCTION add( S1, S2 )
  implicit none
  TYPE (my_taylor) add
```

```

    TYPE (my_taylor), INTENT (IN) :: S1, S2

    add%a=S1%a + S2%a

    call clean(add)
END FUNCTION add

FUNCTION subs( S1, S2 )
    implicit none
    TYPE (my_taylor) subs
    TYPE (my_taylor), INTENT (IN) :: S1, S2

    subs%a=S1%a - S2%a

    call clean(subs)
END FUNCTION subs

```

This is exactly Eq. (12). We encourage the reader to compile the files and run the main program.

4 DA and TPSA maps

The code for this section is located at `z_track_da_tpsa.f90`.

A code like TC always produces TPSA objects by default. To make the explanations simple, we will assume here that TC is tracking for one turn in a ring. The closed orbit in that case is a natural special orbit demanded by theory. For example, all textbooks assume some version of Hill's equation **around the ideal closed orbit** when discussing Courant-Snyder theory.

Calling this orbit f — for fixed point — we have:

$$f = TC(f) \quad (15)$$

We now, via polymorphism, track the following ray z_0 :

$$z_0 = f + \Delta \quad (16)$$

Δ is an array of infinitesimals:

$$\Delta = (\Delta_1, \dots, \Delta_{nv}) \quad \text{where } \Delta_k^{no+1} = 0 \quad (17)$$

If we substitute Eq. (16) in $TC(z)$, we get:

$$TC(f + \Delta) = TC(f) + t_f(\Delta) = f + t_f(\Delta) \quad (18)$$

$t_f(\Delta)$ is a (vector) polynomial in Δ of maximum degree no and such that $t_f(0) = 0$

We can evaluate TC at a different ray not involving the closed orbit f , for example, we can use some arbitrary input in the units of TC:

$$TC(z + \Delta) = TC(z) + t_z(\Delta) = z_1 + t_z(\Delta) \quad (19)$$

In Eq. (18) and Eq. (19), the variable Δ represents a different expansion. If we want Δ to represent the same variable, we need to translate these expressions:

$$m_f(\Delta) = f + t_f(\Delta - f) \quad \text{and} \quad m_z(\Delta) = z_1 + t_z(\Delta - z) \quad (20)$$

In Eq. (20), the maps m_f and m_z are the same if and only if $no = \infty$. For example, we have:

$$m_f(f) = f = m_z(f) + O(|z - f|^{no+1}) \quad (21)$$

Eq. (21) is again exposing a symptom to TPSA maps: inconstant in the order no is finite.

Next we see how to such maps can be concatenated.

4.1 Concatenating two TPSA maps

Consider two TPSA maps:

$$m_{w_0}(\Delta) = w_1 + M_{w_0}(\Delta - w_0) \quad \text{and} \quad n_{z_0}(\Delta) = z_1 + N_{z_0}(\Delta - z_0) \quad (22)$$

For the record here, in FPP, the map m_{w_0} of Eq. (22) is stored as follows:

$$\begin{aligned} &\text{type(c_damap) m} \quad | \text{ Here nv=nd2 + \# of parameters} \\ &\cdot \\ &\text{m\%x0(1:nd2)=w0} \quad | \text{ these are } \mathbf{complex(dp)}, \text{ nd2 is the size of phase space} \\ &\text{m\%v(1:nd2) = w1(1:nd2)+M_{w0}(\Delta(1:nv))} \quad | \text{ these are complex Taylor, i.e., in Berz's } {}_{no}D_{nv} \end{aligned} \quad (23)$$

We compute now the map $t = m \circ n$:

$$\begin{aligned} t &= (m_{w_0} \circ n_{z_0})(\Delta) \\ &= w_1 + M_{w_0}(n_{z_0}(\Delta) - w_0) \\ &= w_1 + M_{w_0}(N_{z_0}(\Delta - z_0) + z_1 - w_0) \end{aligned} \quad (24)$$

This operation is done in FPP between two **c_damap**'s using the operator **.o**.

4.2 Inverse of a TPSA map in terms of a DA map

The inverse of a DA map is well known. First one inverses the linear part, a matrix, and then one inverses the nonlinear part by an iterative method that has a finite number of steps, namely no at most. This routine was programmed by Berz and is in **c_dabnew.f90**. In FPP is called as follows:

```

type(c_damap) m, m_inverse
.
.
m_inverse= m**(-1)
.
.

```

We work out the TPSA inverse of m_{w_0} of Eq. (22). To do so we solve the following equation for y in terms of x :

$$\begin{aligned}
m_{w_0}(x) &= w_1 + M_{w_0}(x - w_0) = y \\
&\Rightarrow x = M_{w_0}^{-1}(y - w_1) + w_0 \\
\text{or } m_{w_0}^{-1}(x) &= M_{w_0}^{-1}(x - w_1) + w_0
\end{aligned} \tag{25}$$

In FPP, the TPSA inverse is invoked by the following call:

```

type(c_damap) m, m_tpsa_inverse
.
.
m_tpsa_inverse= m.oo.(-1)
.
.

```

4.3 Concatenating two DA maps using their TPSA representation

In a “DA” situation, the exit value of the first map must be the entrance value of the second map, i.e., they must be evaluated on the same orbit. Therefore we must have $z_1 = w_0$:

$$m_{w_0}(\Delta) = w_1 + M_{w_0}(\Delta - w_0) \quad \text{and} \quad n_{z_0}(\Delta) = w_0 + N_{z_0}(\Delta - z_0) \tag{26}$$

For example the first map could be from the entrance of a wiggler to its center followed by the second half of the wiggler. Obviously, the exit value of n_{z_0} must be the entrance value of the ray of map m_{w_0} . Here we verified, that in this case, we can ignore completely these constant values. In an integrator, this happens completely naturally since we do not deal with **c_damap** but with the rays themselves in polymorphic form, i.e., type **probe_8**.

$$\begin{aligned}
(m_{w_0} \circ n_{z_0})(\Delta) &= w_1 + M_{w_0}(n_{z_0}(\Delta) - w_0) \\
&= w_1 + M_{w_0}(N_{z_0}(\Delta - z_0)) \\
&= w_1 + (M_{w_0} \circ N_{z_0} \circ (I - z_0))(\Delta) \\
&= w_1 + \underbrace{(M_{w_0} \circ N_{z_0})}^{DA \circ}(\Delta - z_0)
\end{aligned} \tag{27}$$

We see in Eq. (27), where $I - z_0$ represents a translation, that only the concatenation of the map around the orbit is necessary, i.e., $M_{w_0} \circ N_{z_0}$. This is why, in FPP, the DA concatenation does

not keep track of the constant parts at all. This is the case, for example, during all the normal form operations: in the linear case for example, all the the matrices are around the closed orbit, no feed-down effects are present and thus constant parts can be ignored in diagonalizing the matrix.

This DA operation is done in FPP between two **c_damap**'s using the operator *****.

4.4 Finding the closed orbit of a one-turn TPSA map

In an integrator such as Bmad or PTC, we normally find the exact closed orbit f . However what if we have a TPSA map m_{w_0} which is **not** around the closed orbit? We need to solve the following equation:

$$m_{w_0}(f) = w_1 + M_{w_0}(f - w_0) = f \quad (28)$$

Eq. (28) into an equation involving a map:

$$\begin{aligned} m_{w_0}(f) &= f \\ w_1 + M_{w_0}(f - w_0) - f &= 0 \end{aligned} \quad (29a)$$

$$\begin{aligned} w_1 + M_{w_0}(f - w_0) - (f - w_0) - w_0 &= 0 \\ w_1 - w_0 + M_{w_0}(f - w_0) - (f - w_0) &= 0 \\ w_1 - w_0 + (M_{w_0} - I)(f - w_0) &= 0 \\ c_{w_0}(f) &= 0 \end{aligned} \quad (29b) \quad (29c)$$

Eq. (29b) is exactly in the TPSA form of our **c_damap**, i.e., the right hand term of Eq. (20). We can solve for the fixed point f :

$$f = c_{w_0}^{-1}(0) \quad (30)$$

Once again, the value of f will depend on the order of truncation no while the fixed point of the integrator is “exact”.

4.5 Computing the DA map from the TPSA map: inconsistent

Consider the map of Eq. (28)

$$m_{w_0}(z) = w_1 + M_{w_0}(z - w_0) \quad (31)$$

and its fixed point given by Eq. (30). We can re-expressed around the fixed point f . It is done by a strange similarity transformation. Consider this representation of the identity map:

$$a_f(z) = f + I(z - f) \quad (32)$$

Eq. (32) is the identity “expressed” around f . The two f 's obviously cancel. We also notice, not too surprisingly, following Eq. (25), we have

$$a_f^{-1}(z) = a_f(z) \quad (33)$$

We are now ready to make the following similarity transformation on m_{w_0} . To do so, we keep the identity explicitly in Eq. (32) and apply twice the concatenation formula of Eq. (24). It is just a matter of substituting carefully variables:

$$(a_f \circ m_{w_0} \circ a_f)(\Delta) = w_1 + M_{w_0}(I(\Delta - f) - w_0 + f) \quad (34a)$$

$$= \left\{ \underbrace{(w_1 + M_{w_0} \circ (I - w_0 + f))}_{\text{DA map around } f} \circ \underbrace{(I - f)}_{\text{shift}} \right\}(\Delta) \quad (34b)$$

In Eq. (34a)⁶, if we use the definition of I , clearly all f 's disappear and we are back where we started. However we use the definition of a **c_damap** and extract $-f$ from the map and use a shift. This is consistent with the definition shown in blue in Eq. (23).

This last formula allows for normal form on TPSA maps. Of course, if $no/ = \infty$ inconsistencies will appear. For example otherwise symplectic maps will become non-symplectic or, worse, radiation effects will be wiped out. This is why we love integrators with DA maps around the true closed orbit.

We now illustrates all of this in a one dimensional example and also with a real map from a ring. Finally we substitute $\Delta = 0$ is the left factor (DA map) of Eq. (34b) and get

$$w_1 + M_{w_0}(-w_0 + f)$$

which is, according to Eq. (29a), precisely the fixed orbit if f is selected according to Eq. (29c).

4.6 Concatenating two “DA” maps from the “code” of Eq. (35)

We provide an actual one-dimensional example using AP. This is a map in one dimension which is the result of the concatenation of two maps. It imitates a ring made of two parts.

$$\begin{aligned} m_1(x) &= 0.05 + \sin(0.5x) + 0.3 \sin^2(x) \\ m_2(x) &= 0.03 + \sin(0.3x) + 0.2 \sin^2(x) \\ m_{12} &= m_2 \circ m_1 \end{aligned} \quad (35)$$

As we can see, $m(0) \neq 0$: therefore the numbers 0.05 and 0.03 represent a deliberate weird placement of a magnet or the inevitable misalignments found in every beam line. Suppose we want the linear properties of this map, in a code like PTC, it is recommended to first solve for the closed orbit,

$$m_{12}(x_0) = x_0 \rightarrow x_0 = 0.05469119581164052 \dots \quad (36)$$

⁶We avoided abuses of notation in Eq. (34a). Some people may want to confuse the identity I with the dummy variable Δ if that helps.

and then we expand the one-turn map around this closed orbit:

$$m_{12}(x_0 + \Delta) = x_0 + m_{12,1}\Delta + m_{12,2}\Delta^2 + \dots \quad (37)$$

The actual “DA” map is made of the coefficients $m_{12,i}$ of Eq. (37). We can compute this map to second order which is very common in ring dynamics: the linear part gives the usual lattice functions and the second order part gives us the sextupoles distortions and/or chromaticities in a real ring. Here is the code fragment:

```
type(c_taylor)  x    ! In PTC, x would be a probe_8

write(6,*) "Imitating PTC: tracking through  "

x=x_closed+(1.d0.cmono.1)
x=sin(x/2.d0)+0.3d0*sin(x)**2+0.05d0
x_closed1=x        ! recording orbit for future use
x=sin(0.3d0*x)+0.2d0*sin(x)**2+0.03d0

call print(x)
```

The result, for **x**, is:

```
Imitating PTC: tracking through

          1, NO =          2, NV =          1, INA =          9
*****
```

I	COEFFICIENT	ORDER	EXPONENTS
	NO = 2 NV = 1		
0	0.5469119581164052E-01	0.0000000000000000	0
1	0.1763235586477631	0.0000000000000000	1
2	0.1533323662801814	0.0000000000000000	2
-3	0.0000000000000000	0.0000000000000000	0

We see that the real part of the Taylor series is the closed orbit indeed.

The code fragment is:

```
! computing map1
x=x_closed+(1.d0.cmono.1)
x=sin(x/2.d0)+0.3d0*sin(x)**2+0.05d0
map1%v(1)=x
! computing map2
x=x_closed1+(1.d0.cmono.1)
x=sin(0.3d0*x)+0.2d0*sin(x)**2+0.03d0
map2%v(1)=x
one_turn_map_AP = map2*map1
Write(6,*) " This is map1 "
call print(map1)
Write(6,*) " This is map2 "
call print(map2)
```

```

write(6,*) "one_turn_map_AP = map2*map1 "
call print(one_turn_map_AP)
!!! Saving DA coefficients to imitate a TRANSPORT-like code
m(1,1)=map1%v(1).sub.'1'
m(1,2)=map1%v(1).sub.'2'
m(2,1)=map2%v(1).sub.'1'
m(2,2)=map2%v(1).sub.'2'
write(6,*) "Coefficients using Taylor Map Multiplication "
write(6,*) m(1,1)*m(2,1), m(2,1)*m(1,2)+m(2,2)*m(1,1)**2

```

and the result is

```

Creating two DA maps : map1 and map2
This is map1
tpsa status for tracking type(c_ray) F
1 Dimensional DA map (around chosen orbit in map%x0)

1, NO = 2, NV = 1, INA = 10
*****

I COEFFICIENT ORDER EXPONENTS
NO = 2 NV = 1
0 0.7823863368603357E-01 0.000000000000000 0
1 0.5325623875161611 0.000000000000000 1
2 0.2947893387720240 0.000000000000000 2
-3 0.000000000000000 0.000000000000000 0
No Spin Matrix
No c_quaternion
No Stochastic Radiation
This is map2
tpsa status for tracking type(c_ray) F
1 Dimensional DA map (around chosen orbit in map%x0)

1, NO = 2, NV = 1, INA = 24
*****

I COEFFICIENT ORDER EXPONENTS
NO = 2 NV = 1
0 0.5469119581164052E-01 0.000000000000000 0
1 0.3310852639633932 0.000000000000000 1
2 0.1965003538431843 0.000000000000000 2
-3 0.000000000000000 0.000000000000000 0
No Spin Matrix
No c_quaternion
No Stochastic Radiation
one_turn_map_AP = map2*map1
tpsa status for tracking type(c_ray) F
1 Dimensional DA map (around chosen orbit in map%x0)

1, NO = 2, NV = 1, INA = 66

```

```

*****
      I   COEFFICIENT          ORDER   EXPONENTS
      NO =      2      NV =      1
0   0.5469119581164052E-01   0.0000000000000000   0
1   0.1763235586477631      0.0000000000000000   1
2   0.1533323662801814      0.0000000000000000   2
-3   0.0000000000000000      0.0000000000000000   0
No Spin Matrix
No c_quaternion
No Stochastic Radiation
Coefficients using Taylor Map Multiplication
0.176323558647763      0.153332366280181

```

Since the maps **map1** and **map2** are around the closed orbit, we expect them to obey the usual rules of DA concatenation which ignore the constant parts. Thus, given $m_{12} = m_2 \circ m_1$,

$$\text{if } m_1(x_0 + \Delta) = x_1 + m_{1,1}\Delta + m_{1,2}\Delta^2 + \dots \quad (38a)$$

$$\text{and } m_2(x_0 + \Delta) = x_2 + m_{2,1}\Delta + m_{2,2}\Delta^2 + \dots \quad (38b)$$

$$\text{then } m_{12}(x_0 + \Delta) = x_0 + m_{12,1}\Delta + m_{12,2}\Delta^2 + \dots \quad (38c)$$

$$\text{where } m_{12,1} = m_{1,1}m_{2,1} \text{ and } m_{12,2} = m_{2,1}m_{1,2} + m_{2,2}m_{1,1}^2 \quad (38d)$$

We see perfect agreements in the numerical results. Now we will turn this into a TPSA concatenation problem.

4.7 Concatenating the two “TPSA” maps from the “code” of Eq. (35)

Let us compute the one-turn map by concatenating the two maps **map1** and **map2** around, respectively, the weird orbits $x_1 = 0.015$ and $x_2 = 0.02$. As we explained before these are the same as the DA maps of section (§4.6) is $no = \infty$ but here $no = 2$.

The map is computed using the code fragment

```

! Creating TPSA maps around the design orbit

x1= 0.015d0
map1%x0(1)=x1
x=map1%x0(1)+(1.d0.cmono.1)
map1%v(1)=sin(x/2.d0)+0.3d0*sin(x)**2+0.05d0

x2=.02d0
map2%x0(1)=x2
x=map2%x0(1)+(1.d0.cmono.1)
map2%v(1)=sin(0.3d0*x)+0.2d0*sin(x)**2+0.03d0

!!! multiplying the TPSA maps
map12=map2.o.map1

```

```

x=map12*v(1)+i_*one_turn_map_AP*v(1)
write(6,*) "      The map map12 for one turn"
call print(map12)
write(6,*) "      Comparing the TPSA one-turn map with the DA one-turn map"
write(6,*) "      TPSA coefficients      DA coefficient ",k
call print(x)

```

The results are:

```

      The map map12 for one turn
      tpsa status for tracking type(c_ray)  F
          1 Dimensional DA map (around chosen orbit in map%x0)
Initial orbit for TPSA calculations
(1.500000000000000E-002,0.000000000000000E+000)

          1, NO =      2, NV =      1, INA =      38
*****

      I  COEFFICIENT          ORDER  EXPONENTS
      NO =      2          NV =      1
0  0.4793209256475234E-01    0.000000000000000    0
1  0.1643954713972499      0.000000000000000    1
2  0.1482514114953167      0.000000000000000    2
-3  0.000000000000000      0.000000000000000    0
No Spin Matrix
No c_quaternion
No Stochastic Radiation
      Comparing the TPSA one-turn map with the DA one-turn map
      TPSA coefficients      DA coefficient      0

          1, NO =      2, NV =      1, INA =      9
*****

      I  COEFFICIENT          ORDER  EXPONENTS
      NO =      2          NV =      1
0  0.4793209256475234E-01    0.5469119581164052E-01    0
1  0.1643954713972499      0.1763235586477631    1
2  0.1482514114953167      0.1533323662801814    2
-3  0.000000000000000      0.000000000000000    0

```

The two maps, map12 and one_turn_map_AP, are identical but expressed around different orbits. The map one_turn_map_AP is expressed around the closed orbit. We will use the results of section (§4.4) to move map12 to its fixed point. This is done with the code fragment:

```

type(c_ray) rayon
.
.
.
! TPSA maps re-expressed around the closed orbit !

write(6,*) " closed orbit computation "

```

```

write(6,*) map12%x0(1)
c_w0%x0=map12%x0
c_w0%v(1)=map12%v(1)-(1.d0.cmono.1)-map12%x0(1)
c_w0_inv=c_w0.oo.(-1)

f_map%x0=0
f_map%v(1)=0.d0
f_map=c_w0_inv.o.f_map
f_ray=0
f_ray=c_w0_inv.o.f_ray
call print(c_w0_inv)
call print(f_map)
write(6,*) "exact ", x_closed
x_closed_tpsa=map1%v(1)
write(6,*) "TPSA ", x_closed_tpsa
write(6,*) "f_ray ", f_ray%x(1)

go_to_orbit%v(1)= (1.d0.cmono.1)+x_closed_tpsa
go_to_orbit%x0=x_closed_tpsa

map12=(go_to_orbit.o.map12).o.(go_to_orbit.oo.(-1))

call print(map12)

x=map12%v(1)+i*one_turn_map_AP%v(1)
write(6,*) "      Maps around the TPSA closed orbit "
write(6,*) "      Comparing TPSA one-turn map around the TPSA fixed point "
write(6,*) "      with the DA one-turn map"
write(6,*) "      TPSA coefficients          DA coefficient "

call print(x)

```

The answer for the TPSA map around the approximately computed closed orbit is:

```

      Maps around the TPSA closed orbit
      Comparing TPSA one-turn map around the TPSA fixed point
      with the DA one-turn map
      TPSA coefficients          DA coefficient

      1, NO =      2, NV =      1, INA =      9
      *****

      I  COEFFICIENT          ORDER  EXPONENTS
      NO =      2          NV =      1
0  0.5469069935363461E-01  0.5469119581164052E-01  0
1  0.1761640230032753    0.1763235586477631    1
2  0.1482514114953167    0.1533323662801814    2
-3  0.0000000000000000    0.0000000000000000    0

```

We see that the agreement has improved. Indeed if $no = \infty$, the agreement would be perfect.

This is why a code like COSY-INFINITY usually runs at a high order. If we rerun this example with $no = 10$, we get:

```

Maps around the TPSA closed orbit
Comparing TPSA one-turn map around the TPSA fixed point
with the DA one-turn map
TPSA coefficients      DA coefficient

      1, NO =      10, NV =      1, INA =      17
*****

      I  COEFFICIENT      ORDER  EXPONENTS
      NO =      10      NV =      1
0  0.5469119581164050E-01  0.5469119581164052E-01  0
1  0.1763235586477634    0.1763235586477631    1
2  0.1533323662802094    0.1533323662801814    2
3  0.4375700106665827E-01 0.4375700106455089E-01  3
4 -0.3637622533509953E-01 -0.3637622544112402E-01  4
5 -0.3834044616082886E-01 -0.3834044989384196E-01  5
6 -0.1063392477923387E-01 -0.1063401860744071E-01  6
7  0.1162532131698485E-01 0.1162363855314815E-01  7
8  0.1090970864911106E-01 0.1088862478020678E-01  8
9  0.2833241323816774E-03 0.1079668683861611E-03  9
10 -0.3309462539739653E-02 -0.4174183972224262E-02 10

```

We can see that we are closing on the DA map section (§4.6).

In a kick code or integrator, we can compute maps at a low order while preserving perfect self-consistency provided all the maps are computed around the closed orbit in a ring. Therefore, in an integrator, if you like your model, you are assured of self-consistency.

One additional issue is “symplecticity” which cannot be analyzed with a fake map like that of Eq. (35). This can become a severe issue especially if radiation is turned on: the TPSA maps lack of consistency can be greater than radiation damping, thus erasing a very important effect. This does not happen in a (symplectic) integrator since the maps are always self-consistent.

5 PTC examples of DA vs TPSA maps

The code for this section is located at **z_track_map_code.f90**. If you run the code, you can select case 1,2,3 or 4 which correspond respectively to sections (§5.1), (§5.2), (§5.3) and (§5.4).

5.1 Extracting Taylor orbital maps around the closed orbit: case 1

Now we look at a “PTC” piece of code which mixes, in a trivial but very fundamental way, the analysis part (AP) with the tracking part (TC) of PTC with the specific intent of creating a *bona fide* Taylor series map which approximates the beam line in PTC, i.e., the output of the subroutine **propagate**.

Consider:

```
p=>ring%start
closed_orbit=0
call find_orbit_x(closed_orbit,bmad_state, 1.0e-7_dp, fibre1=p)
write(6,*) " closed orbit "
write(6,"(6(1x,g11.4))") closed_orbit
```

The above code is pure tracking of real numbers. The closed orbit is computed at the start of the ring. The **find_orbit_x** routines finds the closed orbit and returns :

```
closed_orbit
-0.1788E-03 -0.9790E-05 -0.1328E-04 -0.6548E-04 -0.1866E-05 -0.5154E-01
```

The object **Bmad_state**, of type **internal_state**, is a PTC structure where the particulars of Bmad are fed for compatibility : units of Bmad, phase space dimension of 6 for **c_damap**'s, etc. . .

internal_state's are objects which control the initialization interface between TC and AP when *bona fide* Taylor maps are needed for analysis. They do not need to exist and could be left to the user if the interaction between TC and AP was a once-in-a-blue-moon event.

The new code fragment is interesting:

```
select case(case_section)
case(1)
p=>ring%start
call move_to(ring,p,"QF1")    ! Locating QF1 in TC
call make_it_knob(p%magp%bn(1),1) ! PP : making a Polymorph into a knob
call move_to(ring,p,"QF2")    ! Locating QF2 in TC
call make_it_knob(p%magp%an(1),2) ! PP : making a Polymorph into a knob

p=>ring%start
closed_orbit=0
call find_orbit_x(closed_orbit,bmad_state, 1.0e-7_dp, fibre1=p)
write(6,*) " closed orbit "
write(6,"(6(1x,g11.4))") closed_orbit

no=1 ; np=2 ; ! nv=6+2=8
call init(bmad_state,no,np) ! Berz's TPSA package is initialized
```

The TPSA variables will be of order no=1 and the phase space dimension will be six via **Bmad_state**. Additionally, via np=2, the polynomials will have two extra variables—knob 1 and 2. Therefore the total number of variables will be 8. Then it is decided that the dipole components of the first QF1 and QF2 will be the 7th (6+1) and 8th (6+2) variables representing respectively the normal dipole component of QF1 and the skew component of QF2. These things are called knobs and can turned off at will. If they are active, then the dipoles components of these quadrupoles are TPSA variables otherwise they stay **real(8)** variables.

Now we mix TC and AP:

```
type(probe) ray_TC
type(probe_8) ray_8_TC
```

```

type(c_damap)  one_turn_map_AP, identity_AP,two_turn_map_AP
real(dp)  closed_orbit(6)
type(internal_state),target :: Bmad_state
.
.
.

ray_TC=closed_orbit    ! For TC

identity_AP=1    ! For AP

ray_8_TC=ray_TC+identity_AP    ! Connect AP with TC
write(6,*) " The initial x "
call print(ray_8_TC%x(1))
call propagate(ray_8_TC,+bmad_state,fibre1=p) ! TC of PTC proper

one_turn_map_AP=ray_8_TC ! TC into AP : makes a map out of ray_8_TC

write(6,*) "x_final for one turn "
call print(one_turn_map_AP%v(1))

two_turn_map_AP=one_turn_map_AP*one_turn_map_AP
write(6,*) "x_final for two turns : squaring the map "
call print(two_turn_map_AP%v(1))

! Tracking two turns using TC
ray_8_TC=ray_TC+identity_AP    ! Connect AP with TC
call propagate(ray_8_TC,+bmad_state,fibre1=p) ! TC of PTC proper
call propagate(ray_8_TC,+bmad_state,fibre1=p) ! TC of PTC proper
two_turn_map_AP=ray_8_TC ! TC into AP : makes a map out of ray_8_TC
write(6,*) "x_final for two turns : tracking two turns "
call print(two_turn_map_AP%v(1))

```

identity_AP is an AP object of type **c_damap**. It is set to a phase space identity by equating it to 1. Indeed in any code which tracks Taylor maps (COSY-INFINITY, TRANSPORT, MARYLIE, etc...) the initial value of a map must be the identity in 6 dimensions. In the linear case, it amounts to the identity matrix in the 6 orbital variables of Bmad. The first variable is the monomial z_1 representing x , the second variable is z_2 will represent p_x and so on, i.e., the variables of the Bmad phase space. (See Bmad manual)

The next line is crucial: it mixes AP and TC. **ray_8_TC** is a **probe_8**: we feed in it the closed orbit buried in **ray_TC** which is made of **real(8)** and add to this the identity map. This operation reveals Forest intent: generally make useful Taylor series phase space maps from TC. It could have been left to the user. Indeed if a user links TC to a library which finds the linear eigenvalues of a matrix, neither Forest nor the authors of that library would provide the interface: it must be written by the user based on the nature of these matrices. Here the object **Bmad_state**, of type **internal_state**, contains all that is needed to make of TC and AP consistent packages.

So now the polymorphic probe **ray_8_TC** contains a polymorph consistent with the identity map expressed around the closed orbit. The code prints this polynomial:

```

The initial x

etall      1, NO =      1, NV =      8, INA =      29
*****

  I  COEFFICIENT          ORDER  EXPONENTS
    NO =      1          NV =      8
0 -0.1787724612820044E-03    0  0  0  0  0  0  0  0  0
1  1.0000000000000000      1  0  0  0  0  0  0  0  0
-2  0.0000000000000000      0  0  0  0  0  0  0  0  0

```

We recognize the closed orbit value of x and the monomial $1.0 * z_1^1$.

Therefore the tracking will take place correctly around the closed orbit and the feed down effects will be correctly computed. This is to be contrasted with *bona fide* Taylor codes (COSY-INFINITY, TRANSPORT, MARYLIE, etc...) where feed-down effects are not self-consistent⁷. Here they are totally self-consistent with the code.

The next is TC proper: **propagate(ray_8_TC,+Bmad_state,fibre1=p)** tracks through the total beam line— actually one turn in this example. The + sign in front of **Bmad_state** activates the “knobs” connected to QF1 and QF2. In TC, knobs are deactivated by default. This is not true of PP proper.

The next line **one_turn_map_AP=ray_8_TC** sends the final TC structure **ray_8_TC** into a **c_damap**: it connects TC to AP. Finally, we attempt a pure AP operation

```
two_turn_map_AP=one_turn_map_AP*one_turn_map_AP
```

This operation is the concatenation of two “differential algebraic” maps: the constant part is ignored.

This is followed by a two turns tracking of TC. The results are identical to machine precision. This is the virtue of using “DA” maps around the closed orbit in an “kick code” or integrator like TC. We print the results for the skeptics: notice machine precision agreement—only the last two digits are different.

```

x_final for one turn
      1, NO =      1, NV =      8, INA =      230
*****

  I  COEFFICIENT          ORDER  EXPONENTS
    NO =      1          NV =      8
0 -0.1787724612819064E-03    0.0000000000000000      0  0  0  0  0  0  0  0  0
1 -0.3889828486539758      0.0000000000000000      1  0  0  0  0  0  0  0  0
1  11.40736328972829      0.0000000000000000      0  1  0  0  0  0  0  0  0
1 -0.3464662557908923E-02    0.0000000000000000      0  0  1  0  0  0  0  0  0
1 -0.4171271427570414E-01    0.0000000000000000      0  0  0  1  0  0  0  0  0
1  0.6963086125527715E-10    0.0000000000000000      0  0  0  0  1  0  0  0  0
1  0.8036598951947091E-01    0.0000000000000000      0  0  0  0  0  1  0  0  0
1 -4.224142793166476      0.0000000000000000      0  0  0  0  0  0  1  0  0
1 -0.3125492004102120E-05    0.0000000000000000      0  0  0  0  0  0  0  1  0
-9  0.0000000000000000      0.0000000000000000      0  0  0  0  0  0  0  0  0

```

⁷COSY-INFINITY is often more accurate than PTC but is not self-consistent with its own model. In rings, this can be a problem. In a single pass system, it might be better to have accurate inconsistent models with complex fringe effects, then simplistic integrators like TC.

```

x_final for two turns : squaring the map

      1, NO =      1, NV =      8, INA = 179
*****

      I  COEFFICIENT          ORDER  EXPONENTS
      NO =      1          NV =      8
0 -0.1787724612819064E-03    0.0000000000000000    0 0 0 0 0 0 0 0
1 -0.7056565190107400      0.0000000000000000    1 0 0 0 0 0 0 0
1 -8.751690962380659      0.0000000000000000    0 1 0 0 0 0 0 0
1 -0.3542316696944531E-01  0.0000000000000000    0 0 1 0 0 0 0 0
1 0.2562552716914303E-02   0.0000000000000000    0 0 0 1 0 0 0 0
1 0.5610356685840276      0.0000000000000000    0 0 0 0 1 0 0 0
1 0.8726398593300869E-01   0.0000000000000000    0 0 0 0 0 1 0 0
1 -2.218998803166924      0.0000000000000000    0 0 0 0 0 0 1 0
1 -0.1965421389017537E-01  0.0000000000000000    0 0 0 0 0 0 0 1
-9 0.0000000000000000      0.0000000000000000    0 0 0 0 0 0 0 0
x_final for two turns : tracking two turns

      1, NO =      1, NV =      8, INA = 179
*****

      I  COEFFICIENT          ORDER  EXPONENTS
      NO =      1          NV =      8
0 -0.1787724612818773E-03    0.0000000000000000    0 0 0 0 0 0 0 0
1 -0.7056565190107397      0.0000000000000000    1 0 0 0 0 0 0 0
1 -8.751690962380632      0.0000000000000000    0 1 0 0 0 0 0 0
1 -0.3542316696944601E-01  0.0000000000000000    0 0 1 0 0 0 0 0
1 0.2562552716913452E-02   0.0000000000000000    0 0 0 1 0 0 0 0
1 0.5610356685840368      0.0000000000000000    0 0 0 0 1 0 0 0
1 0.8726398593301046E-01   0.0000000000000000    0 0 0 0 0 1 0 0
1 -2.218998803166917      0.0000000000000000    0 0 0 0 0 0 1 0
1 -0.1965421389017552E-01  0.0000000000000000    0 0 0 0 0 0 0 1
-9 0.0000000000000000      0.0000000000000000    0 0 0 0 0 0 0 0

```

5.2 Extracting Taylor Series which are not orbital maps: case 2

Nota Bene : In this section, we call FPP outside the constructs of PTC, namely without the use of **bmad_state**. Of course, we could still use **bmad_state** and thus produce a phase space map with null transverse entry. In this case we waste, in Bmad, 6 TPSA variables. This might be a memory/speed issue if a large number of variables or a higher order are required. Otherwise it is perfectly fine. See section (§5.4) to see how the equivalent calculation is done when running with Bmad variables as Taylor series.

The function **propagate** of TC computes a final position $z^f = (z_1^f, z_2^f, z_3^f, z_4^f)$ in terms of an initial position $z^0 = (z_1^0, z_2^0, z_3^0, z_4^0)$.

Furthermore, we can choose 6 magnets to have TPSA parameters. Namely 3 of them will be normal dipole kicks and 3 of them will be skew dipole kicks.

```

p=>ring%start
call move_to(ring,p,"QF1")    ! Locating QF1 in TC
call make_it_knob(p%magp%bn(1),1) ! PP : making a Polymorph into a knob
call move_to(ring,p,"QF2")    ! Locating QF2 in TC

```

```

call make_it_knob(p%magp%an(1),2) ! PP : making a Polymorph into a knob
call move_to(ring,p,"QD1") ! Locating QD1 in TC
call make_it_knob(p%magp%bn(1),3) ! PP : making a Polymorph into a knob
call move_to(ring,p,"QD2") ! Locating QD2 in TC
call make_it_knob(p%magp%an(1),4) ! PP : making a Polymorph into a knob
call move_to(ring,p,"BEND") ! Locating BEND in TC
call make_it_knob(p%magp%bn(1),5) ! PP : making a Polymorph into a knob
call move_to(ring,p,"BEND1") ! Locating BEND1 in TC
call make_it_knob(p%magp%an(1),6) ! PP : making a Polymorph into a knob

```

Even if z^0 starts as **real(8)**, by virtue of polymorphism, it will become a vector of Taylor series if **propagate** visits any of the above magnets..

Here is the code computing z^f . Notice that in this example we start with the entrance orbit $z^0 = 0$. We will try to fit the output z^f also to 0. None of this will depend on the meaning of TC. It could compute the values of stocks for all that we know.

```

bmad_state=bmad_state+nocavity0 ! turns cavities into drifts

p=>ring%start
closed_orbit=0
call find_orbit_x(closed_orbit,bmad_state, 1.0e-7_dp, fibre1=p)
write(6,*) " closed orbit "
write(6,"(6(1x,g11.4))") closed_orbit

np=6 ! number of free parameters to solve these equations
no=1; nV=NP ; ! nv=6
call c_init_all(no,nv) ! FPP command to initialize the TPSA

call alloc(ct);call alloc(ray_8_TC);

ray_TC=entrance_orbit ! For TC
ray_8_TC=ray_TC ! Connect AP with TC: no identity added
write(6,*) "The variable x = z_1^0 "
call print(ray_8_TC%x(1))
p=>ring%start
call propagate(ray_8_TC,+bmad_state,fibre1=p) ! TC of PTC proper
call print(ray_8_TC%x(1))

```

The important difference is the line **ray_8_TC=ray_TC**: the initial orbit made of 6 **real(8)** numbers is simply put into the polymorphic **probe_8** structure **ray_8_TC**. At this stage, there are no Taylor series in sight. Indeed the code print the initial value of x and it is the simply a **real(8)** unlike the example of section (§5.1):

```

The variable x = z_1^0
0.000000000000000E+000

```

However, TC will encounters some Taylor series during the tracking, namely the dipole components of the magnets QF1, QF2, QD1, QD2, BEND and BEND1. Thus, via polymorphism, a Taylor series in these components will appear as the 1st to 6th variables of the TPSA package.

Additionally, the command to initialize TPSA, call **c_init_all(no,nv)**, is pure FPP and is unaware of the analysis package (symplectic maps) or of the code PTC. Indeed while **propagate** is a PTC command, we could have used any code computing anything for the example of this section and section (§5.3).

The output for the variable $x = z_1$ is

```
The variable x = z_1^f

etall      1, NO =      1, NV =     10, INA =     44
*****

      I  COEFFICIENT                ORDER  EXPONENTS
      NO =      1      NV =     10
0  0.6109701219350949E-02      0  0  0  0  0  0  0  0  0  0  0  0
1  -4.962724533009230          1  0  0  0  0  0  0  0  0  0  0
1  -0.2968892804328157E-05      0  1  0  0  0  0  0  0  0  0  0
1  -1.421420498227908           0  0  1  0  0  0  0  0  0  0  0
1  -0.1231462510798852E-05      0  0  0  1  0  0  0  0  0  0  0
1  -1.116448300584394           0  0  0  0  1  0  0  0  0  0  0
1  -0.4314330647295780E-04      0  0  0  0  0  1  0  0  0  0  0
-7  0.0000000000000000          0  0  0  0  0  0  0  0  0  0  0
```

Naive attempts to create a Taylor map using the standard interface between TC and AP, in this example, will lead to nonsense. Instead we will use the resulting polymorphic **probe_8** to create a kind of closed orbit bump by fitting the final z^f to z^0 :

This is the topic of the next section using the example of this section.

5.3 Fitting the output of section (§5.2): case 3

In section (§5.2), the Taylor series of the output **probe_8** called **ray_8_TC** have 6 variables for the dipole strengths. Consider the following functions

$$G = \frac{1}{2} \sum_{i=1,6} k_i^2 + \sum_{i=1,4} \lambda_i \left(z_i^f(\mathbf{k}) - \mathbf{g}_i \right) \quad (39)$$

The vector $\mathbf{v} = (k_1, k_2, k_3, k_4, k_5, k_6, \lambda_1, \lambda_2, \lambda_3, \lambda_4)$ contains the 6 dipole strengths and 4 Lagrange multipliers. The first term in Eq. (39) is the function we will minimize namely the norm of the total dipole strengths. The second term represents the equations we want to set equal to a goal function namely \mathbf{g} . In our example, they are the values of x , p_x , y , and p_y .

The solutions are found by solving the following set of equations:

$$lagrange_map_ap(\mathbf{v}) = \nabla_v G = 0 \quad (40)$$

lagrange_map_ap is a map in 10 TPSA variables. We can solve with by TPSA inversion since the constant part is significant:

$$\mathbf{v} = \text{lagrange_map_ap}^{-1}(0) \quad (41)$$

If the order of the TPSA was infinite, then we would get an exact solution. Otherwise this is simply the first step of a Newton search. We show the actual algorithm and the results:

```

bmad_state=bmad_state+nocavity0 ! turns cavities into drifts

p=>ring%start
closed_orbit=0
call find_orbit_x(closed_orbit,bmad_state, 1.0e-7_dp, fibre1=p)
write(6,*) " closed orbit "
write(6,"(6(1x,g11.4))") closed_orbit

goal=0.d0
entrance_orbit=0
goal(1:6)=entrance_orbit

do k=1,4      ! performing 4 iterations

    !!!!!!! Part 1 : calling TC !!!!!!!
    neq=4      ! number of equations to solve
    np=6       ! number of free parameters to solve these equations
    no=1; nV=NP ; ! nv=6
    call c_init_all(no,nv) ! FPP command to initialize the TPSA

    call alloc(ct);call alloc(ray_8_TC);

    ray_TC=entrance_orbit ! For TC
    ray_8_TC=ray_TC ! Connect AP with TC: no identity added
    !write(6,*) "The variable x = z_1^0 "
    !call print(ray_8_TC%x(1))
    p=>ring%start
    call propagate(ray_8_TC,+bmad_state,fibre1=p) ! TC of PTC proper
    !call print(ray_8_TC%x(1))

    !!!!!!! Part 2 : saving the relevant Taylor series !!!!!!!

    call ALLOC(tpos,1,NV,0) ! c_universal_taylor
    do i=1,4
        ct=ray_8_TC%x(i)%t ! saving final transverse positions and momenta
        tpos(i)=ct
    enddo
    call kill(ct);call kill(ray_8_TC);

    !!!!!!! Part 3 : creating a map of some sort and using it !!!!!!!

```

```

nV=NP+neq ; ! nv=6+4=10
call c_init_all(no,nv) ! FPP command to initialize the TPSA
call alloc(ct);call alloc(eq);

lagrange_map_ap%n=nv
call alloc(lagrange_map_ap)

do i=1,4
  eq(i)=tpos(i) ! putting the c_universal_taylor into c_taylor
enddo

!!! Construction of Lagrange function
do i=1,np
  lagrange_map_ap%v(i)=1.d0.cmono.i
  do j=np+1,np+neq

    ct=((eq(j-np).d.i)*(1.d0.cmono.j))
    lagrange_map_ap%v(i)=lagrange_map_ap%v(i)+ct
  enddo
enddo

do i=np+1,np+neq
  lagrange_map_ap%v(i)=eq(i-np)-goal(i-np)
enddo

lagrange_map_ap=lagrange_map_ap.oo.(-1)

f_ray=0
f_ray=lagrange_map_ap.o.f_ray

p=>ring%start
call move_to(ring,p,"QF1") ! Locating QF1 in TC
k1=f_ray%x(1)
call add(p,1,1,k1)
call move_to(ring,p,"QF2")
k1=f_ray%x(2)
call add(p,-1,1,k1)
call move_to(ring,p,"QD1") ! Locating QF1 in TC
k1=f_ray%x(3)
call add(p,1,1,k1)
call move_to(ring,p,"QD2") ! Locating QF2 in TC
k1=f_ray%x(4)
call add(p,-1,1,k1)
call move_to(ring,p,"BEND") ! Locating QF2 in TC
k1=f_ray%x(5)
call add(p,1,1,k1)
call move_to(ring,p,"BEND1") ! Locating QF2 in TC
k1=f_ray%x(6)
call add(p,-1,1,k1)

```

```

p=>ring%start

ray_TC=entrance_orbit    !   For TC

call propagate(ray_TC,bmad_state,fibre1=p) !   TC of PTC proper

write(6,*) " exit orbit "
write(6,"(4(1x,g11.4))") ray_TC%x(1:4)
call kill(lagrange_map_ap);call kill(ct);call kill(eq);call kill(tpos);

enddo

```

This code fragment has two parts:

1. In the first part, TC is called with the FPP initialization `call c_init_all(no,nv)` with `nv=6`.
2. In the second part, some Taylor series are saved for future used in 4 `c_universal_taylor`'s. These are the Taylor series for the transverse phase space as a function of 6 dipole strengths.
3. A map is created to fit the final positions and momenta reconstructed from the 4 `c_universal_taylor`'s. FPP is initialized with `nv=10`.

First we are taking the derivative of the output of the orbital ray. Secondly we multiply it by **(1.d0.mono.j)** which represents the variables $v_{7,8,9,10}$, i.e., the Lagrange multipliers. There is no chance in hell that this could have been guessed by the programmers of either PTC or Bmad. This map is truly a construction of the user and is not the output of PTC. It is created from the output of PTC the same way a matrix can be computed from the output of an ordinary **real(8)** code via numerical differentiation. What for? Up to the user.

Here is the result of 4 iterations with `no=1`:

```

exit orbit
0.5673E-03  0.4982E-04 -0.1294E-06  0.4597E-08
exit orbit
0.1903E-04 -0.2253E-07 -0.1233E-09  0.1115E-08
exit orbit
0.6044E-09  0.5405E-09 -0.1040E-11 -0.1279E-12
exit orbit
0.1130E-14 -0.3989E-16  0.1440E-19  0.5051E-19

```

With `no=5`, the convergence takes two iterations:

```

exit orbit
-0.1216E-06  0.9864E-08  0.1979E-09  0.6521E-10
exit orbit
-0.1139E-15  0.1102E-16 -0.2711E-19 -0.1347E-19

```

In conclusion, the subroutine **propagate** returns Taylor series which have no apparent special meaning. The user creates in this case a map which the author of PTC, Etienne Forest, could never have anticipated. For this reason, the creation of this Lagrangian-Newton map is entirely the responsibility of the user.

On the other hand, in section (§5.1), the code TC was initialized with the construct

```
identity_AP=1 ! For AP
ray_8_TC=ray_TC+identity_AP ! Connect AP with TC
```

This construction is provided by PTC under the assumption that Taylor maps produced by PTC are the usual phase space maps. The **probe_8** is constructed by adding phase space identity to the closed orbit or entrance orbit. In that sense, PTC tracks phase space maps because of the default interface between TC and FPP.

In fact, as we pointed out, not only the identity can be added but any canonical transformation which represent the shape of a beam or lattice functions— linear, nonlinear, spin, etc. . .

But it is important to remember that any change of variables within PTC involves elements of Berz’s TPSA algebra $_{no}D_{nv}$ and manipulations which are identical to the manipulations of **real(8)**. There are no Taylor maps, no **c_damap**.

5.4 Fitting the orbital ray and the tunes: case 4

This example is a more in tune (pun intended) with the usual usage of PTC. Suppose we want to fit the final position of the ray, as in section (§5.3), as well as the transverse tunes and the phase slip. Then, as in Eq. (39), a contracting map can be constructed from a Lagrange function:

$$G = \frac{1}{2} \sum_{i=1,12} k_i^2 + \sum_{i=1,3} \mu_i (v_i(\mathbf{k}) - v_{0i}) + \sum_{i=1,4} \lambda_i (z_i^f(\mathbf{k}) - \mathbf{g}_i) \quad (42)$$

This time the vector $\mathbf{v} = (k_1, \dots, k_{12}, \mu_1, \mu_2, \mu_3, \lambda_1, \lambda_2, \lambda_3, \lambda_4)$ contains the 12 dipole strengths, 3 Lagrange multipliers for the tunes and phase slip and finally 4 Lagrange multipliers for the orbit.

The code is similar to the code of section (§5.3). However this time a “real map” is computed with 6 phase space variables (Bmad) and 12 parameters for a total of 18 variables. This map is normalized and the transverse tunes in **phase(1:2)** and the phase slip in **phase(3)** are extracted.

In part 2, the equations to solve are saved via the **c_universal_taylor**’s **tpos(:)**. Finally the Lagrange map with the 19 variables of \mathbf{v} is computed and inverted as part of the Newton search.

Here is the code. This concludes our discussion on “Taylor maps” coming out of TC.

```
p=>ring%start
call move_to(ring,p,"QF1") ! Locating QF1 in TC
call make_it_knob(p%magp%bn(2),1) ! PP : making a Polymorph into a knob
call move_to(ring,p,"QF2") ! Locating QF2 in TC
call make_it_knob(p%magp%an(2),2) ! PP : making a Polymorph into a knob
call move_to(ring,p,"QD1") ! Locating QD1 in TC
call make_it_knob(p%magp%bn(2),3) ! PP : making a Polymorph into a knob
call move_to(ring,p,"QD2") ! Locating QD2 in TC
call make_it_knob(p%magp%an(2),4) ! PP : making a Polymorph into a knob
call move_to(ring,p,"BEND") ! Locating BEND in TC
call make_it_knob(p%magp%bn(2),5) ! PP : making a Polymorph into a knob
call move_to(ring,p,"BEND1") ! Locating BEND1 in TC
call make_it_knob(p%magp%an(2),6) ! PP : making a Polymorph into a knob

p=>ring%start
call move_to(ring,p,"QF1") ! Locating QF1 in TC
call make_it_knob(p%magp%bn(1),7) ! PP : making a Polymorph into a knob
```

```

call move_to(ring,p,"QF2")      ! Locating QF2 in TC
call make_it_knob(p%magp%an(1),8) ! PP : making a Polymorph into a knob
call move_to(ring,p,"QD1")      ! Locating QD1 in TC
call make_it_knob(p%magp%bn(1),9) ! PP : making a Polymorph into a knob
call move_to(ring,p,"QD2")      ! Locating QD2 in TC
call make_it_knob(p%magp%an(1),10) ! PP : making a Polymorph into a knob
call move_to(ring,p,"BEND")      ! Locating BEND in TC
call make_it_knob(p%magp%bn(1),11) ! PP : making a Polymorph into a knob
call move_to(ring,p,"BEND1")     ! Locating BEND1 in TC
call make_it_knob(p%magp%an(1),12) ! PP : making a Polymorph into a knob

write(6,*) " %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%"

bmad_state=bmad_state+nocavity0

p=>ring%start
closed_orbit=0
call find_orbit_x(closed_orbit,bmad_state, 1.0e-7_dp, fibre1=p)
write(6,*) " closed orbit "
write(6,*(6(1x,g11.4))) closed_orbit

goal=0.d0
entrance_orbit=closed_orbit
goal(1)=0.28d0
goal(2)=0.79d0
goal(3)=(-1)**ndpt_bmad*2.5d-2
goal(4:7)=entrance_orbit(1:4)

do k=1,8

!!!!!! Part 1 : calling TC !!!!!
neq=7      ! number of equations to solve
np=12      ! number of free parameters to solve these equations
no=2;      ! nv=6+12=18
call init(bmad_state,no,np) ! Berz's TPSA package is initialized
nv=c_%nv   !
call alloc(ct)
call alloc(identity_AP,one_turn_map_AP);call alloc(normal_form);
call alloc(ray_8_TC);call alloc(phase);call alloc(eq)
p=>ring%start

ray_TC=entrance_orbit ! For TC
identity_AP=1
ray_8_TC=ray_TC + identity_AP ! Connect AP with TC: identity added

p=>ring%start
call propagate(ray_8_TC,+bmad_state,fibre1=p) ! TC of PTC proper

one_turn_map_AP=ray_8_TC

! compute 2 tunes and the phase slip
call c_normal(one_turn_map_AP,normal_form,phase=phase)
ray_TC=ray_8_TC
write(6,*(3(1x,g17.10,1x))) normal_form%tune(1:3)
write(6,*(6(1x,g17.10,1x))) ray_TC%x(1:6)
identity_AP=0

phase(3)=phase(3).d.(5+ndpt_bmad) ! compute phase slip dbeta*t/ddelta

phase(1)=(phase(1).o.identity_AP)<=6 ! removing delta dependence
phase(2)=(phase(2).o.identity_AP)<=6 ! removing delta dependence
phase(3)=(phase(3).o.identity_AP)<=6 ! removing delta dependence

eq(1)=phase(1)-goal(1) ! tune x
eq(2)=phase(2)-goal(2) ! tune y
eq(3)=phase(3)-goal(3) ! pahse slip

```

```

do i=1,4
ct=ray_8_TC%x(i)%t
eq(3+i)=((ct.o.identity_AP)<=6)-goal(3+i)
enddo

!!!!!! Part 2 : saving the relevant Taylor series !!!!!
call ALLLOC(tpos,1,NV,0)
do i=1,7
tpos(i)=eq(i)
enddo

call kill(identity_AP,one_turn_map_AP);call kill(normal_form);
call kill(ray_8_TC);call kill(phase);call kill(eq);call kill(ct) ;
!!!!!! Part 3 : creating a map of some sort and using it !!!!!

neq=7      ! number of equations to solve
np=12      ! number of free parameters to solve these equations
no=no-1; nv=NP+neq ; ! nv=7+12=19
call c_init_all(no,nv) ! FPP command to initialize the TPSA
lagrange_map_ap%n=nV ! size of the c_damap must be explicitly stated
call alloc(ct);call alloc(eq);call alloc(lagrange_map_ap);
do i=1,7
eq(i)=tpos(i)
enddo
!!! Construction of Lagrange function
do i=1,np
lagrange_map_ap%v(i)=1.d0.cmono.i
do j=np+1,np+neq
ct=(eq(j-np).d.i)*(1.d0.cmono.j)
lagrange_map_ap%v(i)=lagrange_map_ap%v(i)+ct
enddo
enddo

do i=np+1,np+neq
lagrange_map_ap%v(i)=eq(i-np)
enddo

lagrange_map_ap=lagrange_map_ap.oo.(-1)

f_ray=0
f_ray=lagrange_map_ap.o.f_ray

p=>ring%start
call move_to(ring,p,"QF1") ! Locating QF1 in TC
k1=f_ray%x(1)
call add(p,2,1,k1)
call move_to(ring,p,"QF2")
k1=f_ray%x(2)
call add(p,-2,1,k1)
call move_to(ring,p,"QD1") ! Locating QF1 in TC
k1=f_ray%x(3)
call add(p,2,1,k1)
call move_to(ring,p,"QD2") ! Locating QF2 in TC
k1=f_ray%x(4)
call add(p,-2,1,k1)
call move_to(ring,p,"BEND") ! Locating QF2 in TC
k1=f_ray%x(5)
call add(p,2,1,k1)
call move_to(ring,p,"BEND1") ! Locating QF2 in TC
k1=f_ray%x(6)
call add(p,-2,1,k1)

p=>ring%start
call move_to(ring,p,"QF1") ! Locating QF1 in TC
k1=f_ray%x(7)
call add(p,1,1,k1)

```

```

call move_to(ring,p,"QF2")      ! Locating QF2 in TC
k1=f_ray%x(8)
call add(p,-1,1,k1)
call move_to(ring,p,"QD1")      ! Locating QD1 in TC
k1=f_ray%x(9)
call add(p,1,1,k1)
call move_to(ring,p,"QD2")      ! Locating QD2 in TC
k1=f_ray%x(10)
call add(p,-1,1,k1)
call move_to(ring,p,"BEND")      ! Locating BEND in TC
k1=f_ray%x(11)
call add(p,1,1,k1)
call move_to(ring,p,"BEND1")     ! Locating BEND1 in TC
k1=f_ray%x(12)
call add(p,-1,1,k1)

call kill(ct) ;call kill(eq);call kill(lagrange_map_ap);
enddo

```

In this code we fit the orbit to the original closed orbit.

The results are for the tunes, phase slip and the orbit:

0.2828310304	0.7875313802	-0.2508933816E-01	
0.4575879602E-02	-0.8650459066E-05	-0.1701393632E-04	-0.4623033694E-04
-0.1176909853E-02	0.000000000		
0.2799916973	0.7900014703	-0.2499706314E-01	
0.4581594167E-02	-0.8590151609E-05	-0.1700070068E-04	-0.4623484201E-04
-0.1214079405E-02	0.000000000		
0.2799981589	0.7900002081	-0.2500013027E-01	
0.4575879632E-02	-0.8650379343E-05	-0.1701358606E-04	-0.4623024223E-04
-0.1212988306E-02	0.000000000		
0.2799999976	0.7899999994	-0.2500000017E-01	
0.4575879600E-02	-0.8650459057E-05	-0.1701393633E-04	-0.4623033694E-04
-0.1213016115E-02	0.000000000		
0.2800000000	0.7900000000	-0.2500000000E-01	
0.4575879602E-02	-0.8650459066E-05	-0.1701393632E-04	-0.4623033694E-04
-0.1213016151E-02	0.000000000		
0.2800000000	0.7900000000	-0.2500000000E-01	
0.4575879602E-02	-0.8650459067E-05	-0.1701393632E-04	-0.4623033694E-04
-0.1213016151E-02	0.000000000		
0.2800000000	0.7900000000	-0.2500000000E-01	
0.4575879602E-02	-0.8650459066E-05	-0.1701393632E-04	-0.4623033694E-04
-0.1213016151E-02	0.000000000		
0.2800000000	0.7900000000	-0.2500000000E-01	
0.4575879602E-02	-0.8650459066E-05	-0.1701393632E-04	-0.4623033694E-04
-0.1213016151E-02	0.000000000		

6 Normalizing a TPSA map

The code for this section is located at `z_track_normal_tpsa.f90`.

6.1 Normalizing as a DA map around the closed orbit

Here we run a code where we can choose to get a one-turn map around the closed orbit (DA map) or around the orbit $x = 0$ which in this ring would correspond to the so-called “design orbit”. As in section (§5.1) we used to knobs corresponding to quadrupole components:

```
p=>ring%start
call move_to(ring,p,"QF1")    ! Locating QF1 in TC
call make_it_knob(p%magp%bn(2),1) ! PP : making a Polymorph into a knob
call move_to(ring,p,"QF2")    ! Locating QF2 in TC
call make_it_knob(p%magp%an(2),2) ! PP : making a Polymorph into a knob
```

The next step is to decide whether we want a DA map or a TPSA map around the so-called “design orbit” **x0=0** here:

```
bmad_state=only_4d
.
.
.
p=>ring%start
closed_orbit=0
call find_orbit_x(closed_orbit,bmad_state, 1.0e-7_dp, fibre1=p)
write(6,*) " closed orbit "
write(6,"(6(1x,g11.4))") closed_orbit
x0=closed_orbit

write(6,*) " For TPSA map around f=(0,...,0) type 1 "
write(6,*) " For DA map around closed orbit type 0 "
read(5,*) ignore_closed_orbit
write(6,*) " Give order no "
read(5,*) no
if(ignore_closed_orbit==1) then
  closed_orbit=0
endif
```

We first show the results for the DA map:

```
closed orbit
0.4576E-02 -0.8650E-05 -0.1701E-04 -0.4623E-04  0.000  0.000
For TPSA map around f=(0,...,0) type 1
For DA map around closed orbit type 0
0
Give order no
2
Transverse tunes
0.2828310304 0.7875313802
Dampings (numerical noise)
-0.4329869796E-14 0.1332267630E-14

z_1-component of the Linear Vector Field in Phasors Variables

1, NO = 3, NV = 6, INA = 358
*****
```

```

      I   COEFFICIENT      ORDER   EXPONENTS
      NO =      3      NV =      6
      1   0.0000000000000000      -1.777079774508286      1 0 0 0 0 0
      -1   0.0000000000000000      0.000000000000000      0 0 0 0 0 0

z_1-component of the Non-Linear Vector Field in Phasors Variables (2nd order)

      1, NO =      3, NV =      6, INA = 659
*****
      I   COEFFICIENT      ORDER   EXPONENTS
      NO =      3      NV =      6
      2   0.0000000000000000      -2.580306677113468      1 0 0 0 1 0
      2   0.0000000000000000      0.3425829877097634E-01      1 0 0 0 0 1
      3   0.0000000000000000      -2900.949436382287      2 1 0 0 0 0
      3   0.0000000000000000      6556.211092278534      1 0 1 1 0 0
      3   0.0000000000000000      -0.2020888563626094      1 0 0 0 2 0
      3   0.0000000000000000      -0.2080839310516064      1 0 0 0 1 1
      3   0.0000000000000000      5.902822986039759      1 0 0 0 0 2
      -7   0.0000000000000000      0.000000000000000      0 0 0 0 0 0

```

In the above example, the vector field is given by:

$$F \cdot \nabla = i \left\{ -1.777 - 2.580dk_1^n - 0.034dk_2^s - 2900.949 \underbrace{z_1 z_2}_{J_1} + \dots \right\} z_1 \partial_{z_1} + \text{other planes} \quad (43)$$

In fact, it is a purely imaginary vector field: it represents a tune. In fact $1.777079774508286/2/\pi = 0.2828310304 \dots$ which is just the tune in the first plane.

There is no real part in this vector field since this would represent damping. The state of PTC, **bmad_state=only_4d**, is a cavity-less radiation-less, state which restricts Taylor maps to the transverse orbital dimensions as the **4d** in **only_4d** indicates.

6.2 Normalizing as a TPSA map around the (0,0,0,0,0,0)

Because the map is not around the closed orbit, we must first move the TPSA map around the closed orbit using the algorithm of section (§4.4) and the same code as in page 23. This is given by the code:

```

if(ignore_closed_orbit==1) then
!   Compute TPSA closed orbit
one_turn_map_AP%x0(1:c_%nd2)=x0(1:c_%nd2)
c_w0%x0(1:c_%nd2)=x0(1:c_%nd2)

!!! inversion only need in the transverse plane in this example
do i=1,c_%nd2
  c_w0%v(i)=one_turn_map_AP%v(i)-(1.d0.cmono.i)-one_turn_map_AP%x0(i)
enddo

c_w0_inv=c_w0.oo.(-1)

```

```

f_map%x0=0
do i=1,c_%nd2
f_map%v(i)=0.d0
f_map=c_w0_inv.o.f_map
enddo

f_ray=0
f_ray=c_w0_inv.o.f_ray

! Similarity transformation to the closed orbit

go_to_orbit= 1
go_to_orbit%x0(1:c_%nd2)=f_ray%x(1:c_%nd2)
do i=1,c_%nd2
  go_to_orbit%v(i)= go_to_orbit%v(i)+f_ray%x(i)
enddo

one_turn_map_AP=(go_to_orbit.o.one_turn_map_AP).o.(go_to_orbit.o.(-1))

write(6,"(a18,6(1x,g11.4))") "Exact closed orbit",closed_orbit(1:c_%nd2)
write(6,"(a18,6(1x,g11.4))") "TPSA closed orbit",real(f_ray%x(1:c_%nd2))

endif

```

The result of this normalization is to second order:

```

Exact closed orbit  0.4576E-02 -0.8650E-05 -0.1701E-04 -0.4623E-04
TPSA closed orbit  0.4575E-02 -0.8523E-05 -0.1716E-04 -0.4624E-04
EIG6: Eigenvalues off the unit circle!
  1.00159643192902
EIG6: Eigenvalues off the unit circle!
  1.00159643192902
EIG6: Eigenvalues off the unit circle!
  1.00056073888672
EIG6: Eigenvalues off the unit circle!
  1.00056073888672
Transverse tunes
  0.2826834097      0.7872786253
Dampings (numerical noise)
-0.1595158986E-02 -0.5605817314E-03

z_1-component of the Linear Vector Field in Phasors Variables

      1, NO =      3, NV =      6, INA = 358
*****

      I COEFFICIENT      ORDER EXPONENTS
      NO =      3      NV =      6
1  0.1595158986163770E-02 -1.776152246232164      1  0  0  0  0  0
-1  0.0000000000000000      0.0000000000000000      0  0  0  0  0  0

z_1-component of the Non-Linear Vector Field in Phasors Variables (2nd order)

      1, NO =      3, NV =      6, INA = 667
*****

      I COEFFICIENT      ORDER EXPONENTS

```

```

      NO =      3      NV =      6
2  -0.1819669443106595      -2.657937823855120      1  0  0  0  1  0
2  0.1187338977469338E-02      0.3373570996746057E-01      1  0  0  0  0  1
3  1707.209464520280      -2338.602046283265      2  1  0  0  0  0
3  782.8781372860180      6922.042189398233      1  0  1  1  0  0
3  3.114213005812829      -0.5998691420874549      1  0  0  0  2  0
3  -0.2927537938038314E-01      -0.1634680876623557      1  0  0  0  1  1
3  0.7397499373591118E-01      5.985271299438016      1  0  0  0  0  2
-7  0.000000000000000      0.000000000000000      0  0  0  0  0  0

```

One notices the problems: apparitions of damping, i.e., non-symplectic terms. For example, the (anti)-damping in the first plane is **-0.1595158986E-02**. This is an unacceptable artifact of the feed-down being completely wrong. We see also non-linear anti-damping. This is also a phenomenon of non-symplectic integrators.

Of course we can run at a higher order, for example $no = 11$, printing only numbers greater than 10^{-10} :

```

Exact closed orbit  0.4576E-02 -0.8650E-05 -0.1701E-04 -0.4623E-04
TPSA closed orbit  0.4576E-02 -0.8650E-05 -0.1701E-04 -0.4623E-04
Transverse tunes
  0.2828310304      0.7875313802
Dampings (numerical noise)
-0.1043609643E-13  0.2309263891E-13

z_1-component of the Linear Vector Field in Phasors Variables

      1, NO =      11, NV =      6, INA =      494
*****

  I  COEFFICIENT      ORDER  EXPONENTS
      NO =      11      NV =      6
1  0.000000000000000      -1.777079774507927      1  0  0  0  0  0
-1  0.000000000000000      0.000000000000000      0  0  0  0  0  0

z_1-component of the Non-Linear Vector Field in Phasors Variables (2nd order)

      1, NO =      11, NV =      6, INA =      605
*****

  I  COEFFICIENT      ORDER  EXPONENTS
      NO =      11      NV =      6
2  0.000000000000000      -2.580306677112761      1  0  0  0  1  0
2  0.000000000000000      0.3425829877673507E-01      1  0  0  0  0  1
3  0.7402969486021055E-08      -2900.949436547272      2  1  0  0  0  0
3  0.5652109279438409E-06      6556.211092675170      1  0  1  1  0  0
3  -0.2248561335679724E-08      -0.2020888596108968      1  0  0  0  2  0
3  0.6870246124991154E-09      -0.2080839306933067      1  0  0  0  1  1
3  0.000000000000000      5.902822986046178      1  0  0  0  0  2
-7  0.000000000000000      0.000000000000000      0  0  0  0  0  0

```

We see that the situation as improved and approaches the DA result. It is not surprising that users of COSY-INFINITY must run at very higher order in rings. This is not necessary with a symplectic integrator provided all the maps are around the closed orbit, i.e., DA maps.

7 Taylor and Complex Taylor Fundamental Types

The PP of FPP defines two fundamental structures that are the building blocks of many other structures: **Taylor** and **complextaylor**. The **direct** use of either in a tracking program (that is, when doing simulations with PTC) is discouraged. Rather, other types like **real_8** and **complex_8** should be used.

These are used via the polymorphic types **real_8** and **complex_8** in the tracking code TC.

7.1 Initializing TPSA win FPP and PTC

FPP and PTC can function in two modes:

1. Mode ignorant of accelerator phase space maps. In that case, FPP does not know what a normal form is. Dimension of **c_damap** must be specified by the user. You are on your own. This is not recommended if you have an even dimension phase space that represents the dynamics of beams.
2. You have maps of even dimensions with perhaps spin. FPP must know about this: happens with initialization.

7.1.1 Ignorant of PTC initialization mode

In the case of FPP, the following call must be performed:

```
neq=4      ! number of equations to solve
np=6       ! number of free parameters to solve these equations
no=1; nv=NP+neq ; ! nv=6+4=10

call c_init_all(no,nv) ! FPP command to initialize the TPSA

call alloc(ct);call alloc(eq); ! type c_taylor ct and eq(:)
lagrange_map_ap%n=nv ! type c_damap
call alloc(lagrange_map_ap) ! type c_damap
```

This initialization of TPSA and AP creates **nv** variables of order **no**: there is no mention of maps. Thus the number of dimension of **lagrange_map_ap**, a **c_damap**, must be specified in **lagrange_map_ap%n**. Here it has **nv** variables. This number can be from **lagrange_map_ap%n=1** to **lagrange_map_ap%n=nv**. Any attempt to normalized that map would lead to a crash.

7.1.2 Even dimension initialization mode

```
neq=4      ! number of equations to solve
np=6       ! number of free parameters to solve these equations
no=1; nv=NP+neq ; ! nv=6+4=10
```

```
call c_init_all(no,nv)    ! FPP command to initialize the TPSA

call alloc(ct);call alloc(eq);  ! type c_taylor ct and eq(:)
lagrange_map_ap%n=nv    ! type c_damap
call alloc(lagrange_map_ap)  ! type c_damap
```

7.2 Taylor Type

The **taylor** structure overloads the Taylor series of the original real “DA-Package” of Berz. See §8.1. The structure is

```
type taylor
  integer i    ! Pointer to Berz
end type taylor
```

The Berz package uses a positive integer to differentiate different Taylor series and the **taylor** structure just stores a reference integer.

7.3 ComplexTaylor Type

The **complextaylor** structure stores two Taylor series which represent the real and imaginary parts. The structure is:

```
type complextaylor
  type (taylor) r    ! Real part of complex Taylor series.
  type (taylor) i    ! Imaginary part of complex Taylor series.
end type complextaylor
```

7.4 Overloaded Operators for Taylor and ComplexTaylor Types

Overloaded operators for **taylor** and **complextaylor** types include the standard functions like **sin** and **tanh** as well as the operators used in arithmetic expressions **+**, **-**, *****, **/**, ******.

8 Real_8 Type

FPP defines the **taylor** type (§7.3) which holds a Taylor series. Since computations with Taylor series would soon exhaust all the memory of Berz's package, FPP defines a "polymorphic" type called **real_8**. Indeed, in PTC, almost anything can become a Taylor series including multipole strengths, wiggler profiles, voltages, frequencies, etc... This would totally overload the memory of the TPSA package for any lattice with the exception of tiny ones.⁸ In general, a "polymorphic" variable is a variable that can act in different ways depending on the context of the code. In this case, a **real_8** variable can act as if it were a real number or it can act as if it were a Taylor series depending upon how it is initialized. An example program will make this clear.

```
program real_8_example
use pointer_lattice      ! Read in structure definitions, etc.
implicit none

type (real_8) r8         ! Define a real_8 variable named r8
real(dp) x               ! Define a double precision number

!

nice_taylor_print = .true.    ! Nicely formatted "call print" output
call init (only_2d0, 3, 0)    ! Initialize: #Vars = 2, Order = 3

call alloc(r8)              ! Initialize memory for r8

x = 0.1d0
r8 = x                      ! Init r8 to a real => r8 will act as a real.
print "(/,a)", "r8 is now acting as a real:"
call print (r8)              ! Will print a real number.

r8 = 0.7d0 + dz_8(1) + 2*dz_8(2)**3    ! Init r8 as a Taylor series
print "(/,a)", "r8 is now acting as a Taylor series:"
call print(r8)                  ! Will print a Taylor series.

r8 = r8**4    ! Raise the Taylor series to the 4th power
print "(/,a)", "This is r8^4:"
call print (r8)

call kill(r8)
end program
```

The variable **x** is defined as a double precision real number. The line

```
type (real_8) r8
```

defines **r8** as an instance of a **real_8** variable and the line

```
call alloc(r8)
```

⁸The "8" here is an allusion to the fact that double precision numbers are generally represented by 8 bytes and indeed the **dp** parameter defined by FPP/PTC to designate double precision numbers has, on most systems, a value of 8.

initializes **r8**. This initialization must be done before **r8** is used. After **r8** is used, any memory that has been allocated for use with **r8** is reclaimed by calling the **kill** routine.

```
call kill(r8)
```

This illustrates a general rule: All calls to **alloc** must have a corresponding **kill**.⁹ When **r8** is set to the real number **x** in the line¹⁰

```
r8 = x
```

This initialization of **r8** will cause **r8** to act as a real number. This is verified by printing the value of **r8** in the lines

```
print '(/,a)', "r8 is now acting as a real:"  
call print (r8)
```

The output is just a single real number indicating that **r8** is acting as a real:

```
r8 is now acting as a real:"  
0.1000000000000000
```

Notice that the **print** statement uses the Fortran intrinsic print function while the **call print** statement uses the overloaded print subroutine defined by **FPP**.

When **r8** is set to a Taylor series in the line

```
r8 = 0.7d0 + dz_8(1) + 2*dz_8(2)**3 ! Init r8 as a Taylor series
```

this will cause **r8** to act as a Taylor series. To understand how this initialization works, first consider the initialization of **FPP**/**PTC** which was done by the line

```
call init (only_2d0, 3, 0) ! Initialize FPP/PTC. #Vars = 2, Order = 3
```

The first argument, **only_2d0**, is a parameter defined by **PTC** of type **internal_state** (§11).¹¹ When **only_2d0** is used as the first argument to **init**, the number of variables will be two which is appropriate for simulations involving motion along one axis (typically involving phase space (x, p_x)).¹² The second argument, **3**, gives the order at which the Taylor series is truncated to.

⁹Strictly speaking, **kill** is not necessary here since memory cleanup is automatically done at the end of the program. However, in a subroutine or function, all local instances of **real_8** variables must be killed otherwise there will be a memory leak.

¹⁰All sets like this where the variable type on the LHS is different from the RHS is, by necessity, done with an overloaded equal sign.

¹¹When an **internal_state** type is used as the first argument in the overloaded routine **init**, both **FPP** and **PTC** will be initialized.

¹²There is also an **only_4d0** parameter for configuring using 4 variables for simulations with transverse phase space (x, p_x, y, p_y) . However, there is no **only_6d0** parameter since configuring for the full 6D phase space is a bit more complicated (involving consideration like whether there are powered RF cavities or not). If only **FPP** needs to be initialized (as is the case at hand), the initialization here could have been done in the above example via:

```
call init (3, 1,np1=0) ! Init just FPP. Order = 3, #Vars = 2, degrees of freedom = 1
```

or

```
call init (3, 2) ! Init just FPP. Order = 3, #Vars = 2, degrees of freedom = not needed
```

Notice that here the order comes before the number of variables which is the reverse of the order when **init** is called with an **internal_state** as the first argument. In the first instance, the analysis AP is aware that a Taylor map in two variables can be normalized. In the second instance maps can be created but they are generic without any normal form as far as AP is concerned.

$$t = \sum_{i,j}^{0 \leq i+j \leq 3} C_{ij} z_1^i z_2^j \quad (44)$$

where z_1 is the first variable and z_2 is the second variable. **FPP** sets up a **real_8** array named **dz_8** such that **dz_8(N)** represents the N^{th} variable.¹³ Thus in the above code **r8** is initialized to the Taylor series:

$$t = 0.7 + z_1 + 2z_2^3 \quad (45)$$

This is confirmed by printing **r8** after it has been set via the lines

```
print '(/,a)', "r8 is now acting as a Taylor series:"
call print(r8)
```

The output is:

r8 is now acting as a Taylor series:			
Out	Order	Coef	Exponents
	0	0.7000000000000000	0 0
	1	1.0000000000000000	1 0
	3	2.0000000000000000	0 3

Each line in the above output, after the line with dashes, represents one term in the Taylor series. The general form for printing a Taylor term is:

```
<output-index> <order> <coef> <z1-exponent> <z2-exponent>, ...
```

The `<output-index>` is the index of the output variable when there is an array of variables. Here, since `r8` is not an array, the `<output-index>` column is blank. The `<order>` is the order of the term. That is, the sum of the exponents. For example, the last line in the above printout is

3	2.0000000000000000	0	3
---	--------------------	---	---

This line represents the term $2z_1^0z_2^3$ which is order 3. The **<coef>** column is the term coefficient and **<z1-exponent>**, and **<z2-exponent>** collums are the exponents z_1 and z_2 in the term. The number of exponent columns will be equal to the number of variables.

Once `r8` has been initialized, it can be used in expressions. Thus the line

```
r8 = r8**4 ! Raise the Taylor series to the 4th power
```

raises **r8** to the 4th power and puts the result back into **r8**. This is confirmed by the final print which produces

This is r8^4:			
Out	Order	Coef	Exponents

	0	0.24009999999999999	0 0

¹³More accurately, $\mathbf{dz_8}(\mathbf{N})$ is the Taylor series $t = z_j$.

1	1.3720000000000000	1	0
2	2.9400000000000000	2	0
3	2.8000000000000000	3	0
3	2.7439999999999999	0	3

Notice that the map has been truncated so that no term has an order higher than 3 as expected. Expressions using **real_8** variables involve overloaded operators as discussed in section §??.

8.1 Real_8 Under the Hood

The particulars of how the **real_8** structure is defined are generally not of interest to the general user. However, it is instructive to take a quick look. In the **FPP** code the **real_8** structure is defined as:

```
type real_8
  type (taylor) t    ! Used if taylor
  real(dp) r         ! Used if real
  integer kind       ! 0,1,2,3 (1=real,2=taylor,3=taylor knob)
  integer i          ! Used for knobs and special kind=0
  real(dp) s         ! Scaling for knobs and special kind=0
  logical(lp) :: alloc ! True if taylor is allocated in da-package
end type real_8
```

The **t** component of the structure is of type **taylor** (§7.3) and is used if a **real_8** variable is acting as a Taylor series. The **r** component is used if a **real_8** variable is acting as a real number. The **kind** component is an integer that sets the behavior of a **real_8** variable. Besides behaving as **real** or a Taylor series, a **real_8** variable may behave as a "**knob**" which will be explained later. The reason for hiding a Taylor series under the hood is to defer the decision of its use to run time.

This is useful when tracking since manipulating Taylor series is computationally more expensive than using real numbers.

9 Complex_8 Type

The type **complex_8** is the polymorphic version of the **complextaylor** type just as the **real_8** type is the polymorphic version of the **taylor** type.

The type **complex_8** is rarely used in a tracking code since all quantities we compute are ultimately real. However once in a while it is useful to go into complex coordinates temporarily. The **complex_8** type is useful in several cases. For example, when fields are expressed in cylindrical coordinates. In such a case, if $\mathbf{z} = (x, p_x, y, p_y)$, then most intermediate calculations involve a quantity $q = x + iy$. and the complex polymorph is useful.

The definition of **complextaylor** is:

```
type complex_8
  type (complextaylor) t
  complex(dp) r
  logical(lp) alloc
  integer kind
  integer i,j
  complex(dp) s
end type complex_8
```

As in the case of the real polymorph, the **t** component contains the complex Taylor series and the **r** component contains the complex number if the polymorph is not a Taylor series.

10 Real_8 and Complex_8 Functions and Operators

Operators that act on **real_8** and **complex_8** types:

```
exp(t)                ! Exponentiation
log(t)                ! Log
sin(t), cos(t), tan(t) ! Trig functions
asin(t), acos(t), atan(t) ! Inverse trig functions
sinh(t), cosh(t), tanh(t) ! Hyperbolic functions
atan2(ty, tx)
sinx_x(t)
sinhx_x(t)
abs(t)
full_abs(t)???? What is this
dble ???? is this the same as real?
real(ct), aimag(ct)
cmplx(t_re, t_im)
```

Question: Do all functions act on **real_8**, **taylor**, **complex_8**, **complextaylor**?

Include **dz_8**

11 Internal_State Type

Components of the **internal_state** structure define parameters that affect such things as whether RF cavities are considered to be on or off or how phase space variables are treated. The structure definition is:

```
type internal_state
  integer totalpath      ! T => total time or path length is used
  logical(lp) time       ! T => Time is used instead of path length
  logical(lp) radiation  ! T => Radiation is turned on
  logical(lp) nocavity   ! T => Cavity is turned into a drift
  logical(lp) fringe     ! T => Fringe fields on? (mainly for quadrupoles)
  logical(lp) stochastic ! T => Random Stochastic kicks to x(5)
  logical(lp) envelope   ! T => Stochastic envelope terms tracked in probe_8
  logical(lp) para_in    ! T => Parameters in the map are included
  logical(lp) only_4d    ! T => Real_8 Taylor in (x,p_x,y,p_y)
  logical(lp) delta      ! T => Real_8 Taylor in (x,p_x,y,p_y,delta)
  logical(lp) spin       ! T => spin is tracked
  logical(lp) modulation ! T => One modulated family tracked by probe
  logical(lp) only_2d    ! T => Real_8 taylor in (x,p_x)
  logical(lp) full_way   !
end type internal_state
```

For each structure component except **param_in** and **full_way**, there is a global parameter defined

Explain Bmad units

In PTC, when “**time**” units are being used (the **time** component is set true), the orbital phase space is:

$$x(1:6) = \left(x, \frac{p_x}{p_0}, y, \frac{p_y}{p_0}, \frac{\Delta E}{p_0 c}, cT \text{ or } c\Delta T \right) \quad (46)$$

where cT is used for $x(6)$ if the **totalpath** component is set True, and $c\Delta T$ is used for $x(6)$ if **totalpath** is set False.

When **Bmad** units are used, the orbital phase space is:

$$x(1:6) = \left(x, \frac{p_x}{p_0}, y, \frac{p_y}{p_0}, -\beta cT \text{ or } -\beta c\Delta T, \frac{\Delta p}{p_0} \right) \quad (47)$$

where $-\beta cT$ is used for $x(5)$ if the **totalpath** component is set True, and $-\beta c\Delta T$ is used for $x(5)$ if **totalpath** is set False.

With 1-d-f tracking, only the first two phase space coordinates are used. With 2-d-f, only the first four phase space coordinates are used.

where

$$\Delta T = T - T_{ref} \quad (48)$$

12 Other Polymorphic Types: `spinor_8`, `quaternion_8`, and `rf_phasor_8`

The types discussed above are useful for anyone who decides to use FPP to write their own tracking code. In fact there is nothing “tracking” about these types. One could write a code to solve a problem in finance or biology using `real_8`. However, since our ultimate goal is to describe the analysis part of FPP, we need to say a little bit more about some of the structures used in PTC. Here we introduce three.

The **spinor** type is the represents a particle’s spin in (x, y, z) coordinates:

```
type spinor
  real(dp) x(3)  ! x(3) = (s_x, s_y, s_z)    with  |s|=1
end type spinor
```

and the **spinor_8** is the polymorphic equivalent:

```
type spinor_8
  type(real_8) x(3)  ! x(3) = (s_x, s_y, s_z)    with  |s|=1
end type spinor_8
```

The **quaternion** type is used to store the quaternion representing spin transport:

```
type quaternion
  real(dp) x(0:3)
end type quaternion
and the \vn{quaternion_8} is the polymorphic equivalent:
\begin{code}
type quaternion_8
  type(real_8) x(0:3)
end type quaternion_8
```

The **rf_phasor** type is used for RF phase modulation:

```
type rf_phasor
  real(dp) x(2)
  real(dp) om
  real(dp) t
end type rf_phasor
```

and the corresponding **rf_phasor_8** polymorphic equivalent is:

```
type rf_phasor_8
  type(real_8) x(2)    ! The two hands of the clock
  type(real_8) om      ! the omega of the modulation
  real(dp) t           ! the pseudo-time
end type rf_phasor_8
```

These structures are used as components of the **probe** and **probe_8** types (§13) that are used for tracking.

13 Probe and Probe_8 Types

The **probe** and **probe_8** types are used for tracking in **PTC**. The **probe** structure looks like:

```
type probe
  real(dp) x(6)
  type(spinor) s(3)
  type(quaternion) q
  type(rf_phasor) ac(nacmax)
  integer:: nac=0
  ...
end type probe
```

And **probe_8** is the polymorphic equivalent (§3.3):

```
type probe_8
  type(real_8) x(6)           ! Polymorphic orbital ray
  type(spinor_8) s(3)        ! Polymorphic spin s(1:3)
  type(quaternion_8) q       ! Spin transport quaternion
  type(rf_phasor_8) ac(nacmax) ! Modulation of magnet
  integer:: nac=0            ! Number of modulated clocks <= nacmax
  real(dp) E_ij(6,6)         ! Envelope for stochastic radiation
  real(dp) x0(6)             ! Initial ray for TPSA calc with c_damap
  ....
end type probe_8
```

That is, the **x**, **s**, **q** and **ac** components of the **probe** structure are replaced in the **probe_8** structure with their polymorphic analogues. Since **probe_8** can do everything that **probe** does, why bother to define the **probe** structure? The reason is speed as will be discussed below.

The way PTC uses **probe** and **probe_8** is that for a given a PTC tracking routine that uses **probe_8** there is a duplicate tracking routine that uses **probe**. The **probe_8** routine is to be used when tracking is to be done using Taylor maps and the **probe** routine is to be used for tracking ordinary real rays. **Probe** is equivalent to tracking **probe_8** setting the truncation order to 0.

The same routine duplication happens with routines that use **real_8**. In this case the corresponding routine will use a **real(dp)** variable. As an example, consider the subroutine in the example of §14:

```
subroutine trackp(z)
  implicit none
  type(real_8) :: z(2)
  z(1) = z(1) + L*z(2)
  z(2) = z(2) - B - K_q*z(1) - K_s*z(1)**2
end subroutine track
```

This routines computes the effect of a “drift” followed by a multipole “kick” in the jargon of accelerator physicists. The corresponding **real(dp)** version is:

```
subroutine trackr(z)
  implicit none
```

```

real(dp) :: z(2) <----- instead of type(real_8) :: z(2)
z(1)=z(1)+L*z(2)
z(2)=z(2)-B-K_q*z(1)-K_s*z(1)**2
end subroutine track

```

The naming of the two routines **trackp** and **trackr** follow a common PTC convention that routines that involve polymorphic types have a name ending in **p** and corresponding non-polymorphic routines have a name ending in **r**.

13.1 The x(6) component

The **x(6)** component represents the orbital phase space part of the tracked particle.

13.2 The spin and quaternion components

PTC can track spin. There are two ways to track spin: one method uses a regular spin matrix and the other uses a quaternion. Originally, only the matrix based method was implemented. The quaternion representation was subsequently implemented since it is a more efficient representation for the spin and it simplifies the analysis. From the theory of rotations in three dimensions, we know that there is one invariant unit direction and one angle of rotation around this axis. The unit quaternion has exactly the same freedom: four numbers whose squares add up to one. Once more we claim that if its polymorphic components are properly initialized, a generic Taylor map for the quaternions emerges. This is described in §??.

For the spin matrix representation, Since there are three independent directions of spin, PTC tracks three directions: this saves time if one wants to construct a spin matrix. The three directions are represented by the three **s(3)** components which are of type **spinor_8**:

```

type spinor_8
  type(real_8) x(3) ! x(3) = (s_x, s_y, s_z) with |s|=1
end type spinor_8

```

For example, if one tracks on the closed orbit, the initial conditions are

$$\begin{aligned}
 s(1) &= (1, 0, 0) \\
 s(2) &= (0, 1, 0) \\
 s(3) &= (0, 0, 1)
 \end{aligned}
 \tag{49}$$

The tracking of these vectors for one turn will allow us to construct the one-turn spin matrix around the closed orbit. Thus if the orbital polymorphs are powered to be appropriate Taylor series in n-d-f (n=1,2, or 3), we can produce a complete approximate 3 by 3 matrix for the spin. This is shown in §??.

13.3 The components of type rf_phasor_8

The **rf_phasor_8** type is somewhat complex to explain but its definition is simple:

```

type rf_phasor_8
  type(real_8) x(2) ! The two hands of the clock
  type(real_8) om    ! the omega of the modulation
  real(dp) t        ! the pseudo-time
end type rf_phasor_8

```

The variables **x(2)** represents a vector rotating at a frequency **om** based on a pseudo-time related to the reference time of the “design” particle. As the the **probe_8** traverses a magnet, in the integration routines, magnets can use that pseudo-clock to modulate their multipole components. In the end, as we will see, the components **rf_phasor_8%x(2)** are used to add two additional dimensions to a Taylor map. This will be explained later when we discuss the types germane to analysis.

13.4 The real components **E_ij(6,6)** and equilibrium moments

The **E_ij(6,6)** structure allows us to store the quantum fluctuations due to radiation. PTC, does not attempt to go beyond linear dynamics when dealing with photon fluctuations. When radiation is present, the **x(6)** polymorphic component of **probe_8** contain the closed orbit (with classical radiation) and the **E_ij(6,6)** component stores the fluctuations $\langle x_i x_j \rangle$ ($i, j = 1, 6$) due to photon emission. Notice that **E_ij** is not polymorphic. Radiation fluctuations are always approximated to zeroth order around the reference orbit.

If a linear matrix M is extracted from **probe_8**, then the one-turn linear map for moments is given by:

$$\Sigma_{\text{final}} = M (\Sigma_{\text{initial}} + E) M^T \quad (50)$$

where superscript **T** indicates transpose and

$$\Sigma_{ij} = \langle x_i x_j \rangle, \quad i, j = 1, \dots, 6. \quad (51)$$

However when a **probe_8** is converted into a **c_damap** with the syntax **c_damap = probe_8**, then E is redefined as:

$$\Sigma_{\text{final}} = M \left(\Sigma_{\text{initial}} + E_{\text{probe}_8} \right) M^T = M \Sigma_{\text{initial}} M^T + E_{\text{c_damap}}. \quad (52)$$

Thus, in FPP, the equation from the moments is:

$$\Sigma_{\text{final}} = M \Sigma_{\text{initial}} M^T + E, \quad (53)$$

where E has been redefined.

To get the equilibrium moments, we can first diagonalized the matrix M :

$$M = B\Lambda B^{-1} \quad \text{where}$$

$$\Lambda = \begin{pmatrix} \lambda_1 & 0 & 0 & 0 & 0 & 0 \\ 0 & \lambda_2 & 0 & 0 & 0 & 0 \\ 0 & 0 & \lambda_3 & 0 & 0 & 0 \\ 0 & 0 & 0 & \lambda_4 & 0 & 0 \\ 0 & 0 & 0 & 0 & \lambda_5 & 0 \\ 0 & 0 & 0 & 0 & 0 & \lambda_6 \end{pmatrix} \quad \text{and} \quad \begin{matrix} \lambda_1 = \exp(-\alpha_1 - i2\pi\mu_1) \\ \lambda_2 = \exp(-\alpha_1 + i2\pi\mu_1) \\ \lambda_3 = \exp(-\alpha_2 - i2\pi\mu_2) \\ \lambda_4 = \exp(-\alpha_2 + i2\pi\mu_2) \\ \lambda_5 = \exp(-\alpha_3 - i2\pi\mu_3) \\ \lambda_6 = \exp(-\alpha_3 + i2\pi\mu_3) \end{matrix} . \quad (54)$$

We can apply the transformation B on Eq. (53):

$$\begin{aligned} B\Sigma_{\text{final}}B^T &= BM\Sigma_{\text{initial}}M^TB^T + BEB^T \\ \sigma_{\text{final}} &= \Lambda\sigma\Lambda + \varepsilon \end{aligned} \quad (55)$$

And since Λ is diagonal, we can easily get the equilibrium σ^{inf} in this basis:

$$\begin{aligned} \sigma^{\infty} &= \Lambda\sigma^{\infty}\Lambda + \varepsilon \\ &\Downarrow \\ \sigma_{ij}^{\infty} &= \frac{\varepsilon_{ij}}{1 - \lambda_i\lambda_j} \end{aligned} \quad (56)$$

The terms σ_{12}, σ_{34} and σ_{56} correspond to the so-called equilibrium emittances and they dominate when damping is small and when the map is far from linear resonances. For example, the horizontal emittance is

$$\sigma_{12}^{\infty} = \frac{\varepsilon_{12}}{1 - e^{-2\alpha_1}} \approx \frac{\varepsilon_{12}}{2\alpha_1}. \quad (57)$$

ε_{12} is called, in accelerator jargon, the horizontal H -function. It is the fluctuation of the horizontal invariant summed over the entire machine. The final beam sizes are given by:

$$\Sigma^{\infty} = B^{-1}\sigma^{\infty}B^{-1T}. \quad (58)$$

In §?? we explain how one can use E in stochastic tracking.

13.5 Real(dp) type probe specific to PTC

In theory, it is possible to have a code which always uses the polymorphs **real_8** and nothing else. However this is not what PTC does due to computational speed considerations. To see this consider the following code fragment

```
type(real_8) a,b,c
.
.
c=a+b
```

How many internal questions does the $+$ operation requires? First it must decide if **a** is real, Taylor or knob? The same thing applies to the polymorph **b**. On the basis of the answer, it must branch into 9 possibilities before it can even start to compute this sum. This overhead slows down a polymorphic calculation even if all the variables are real. To get around this, PTC has a type **probe**...

As we said, PTC tracks **probe** or **probe_8**. It is very easy to modify the above routines to mimic this feature of PTC. This is done in the module **my_code** in the file **z_my_code.f90**. Notice that the cell is repeated **nlat** times which is defaulted to 4:

```

module my_code
  use tree_element_module
  implicit none
  private trackr, trackp
  type(real_8) :: L ,B, K_q , K_s
  real(dp) :: L0 , B0, K_q0 , K_s0
  real(dp) par(4)
  integer ip(4)
  integer :: nlat = 4

  interface track
    module procedure trackr
    module procedure trackp
  end interface

  contains
    .
    .
    .
    subroutine trackr(p) ! for probe
      implicit none
      type(probe) :: p
      integer i
      do i=1,nlat
        p%x(1)=p%x(1)+L0*p%x(2)
        p%x(2)=p%x(2)-B0-K_q0*p%x(1)-K_s0*p%x(1)**2
      enddo
    end subroutine trackr

    subroutine trackp(p) ! for probe_8
      implicit none
      type(probe_8) :: p
      integer i
      do i=1,nlat
        p%x(1)=p%x(1)+L*p%x(2)
        p%x(2)=p%x(2)-B-K_q*p%x(1)-K_s*p%x(1)**2
      enddo
    end subroutine trackp

```



```

      .
      .
      .
end module my_code

```

Then a call to **track(p)** will either call

- **trackr(p)** if **p** is a **probe**
- or **trackp(p)** if **p** is a **probe_8**

If we call **track(p)** where **p** is a **probe_8**, then the resulting **p** could be a Taylor series which approximates the true map¹⁴ of the code.

For example, in §14, we got the following results for the final polymorphs:

```

Properties, NO =      2, NV =      2, INA =      20
*****

  1   1.0000000000000000      1   0
  1   1.0000000000000000      0   1

Properties, NO =      2, NV =      2, INA =      21
*****

  1  -0.1000000000000000      1   0
  1   0.9000000000000000      0   1

```

It is clear that one could deduce from the above result:

$$\mathbf{z} = \begin{pmatrix} 1 & 1 \\ -0.1 & 0.9 \end{pmatrix} \begin{pmatrix} z_1 \\ z_2 \end{pmatrix} + O(z^2) \quad (59)$$

Therefore we could say that **z** or equivalently a **probe_8** is a “Taylor map.” But this is not done in PTC for several reasons:

1. The variables (z_1, z_2) could be infinitesimal with respect to machine parameters, in which case any attempt to concatenate the matrix is pure nonsense.
2. One should not confuse a set with an algebraic structure which the set itself.

Item 2 requires an explanation. Take for example a pair of real numbers from the set $\mathbb{R} \times \mathbb{R}$. A priori we have no idea what structures are imposed on this pair of numbers. Indeed the structure could be a complex number field, a ring of differentials (running TPSA to order 1 with one parameter), a one-dimensional complex vector space, a two dimensional real vector space, a twice infinite dimensional vector space on the field of rationals, etc... In a code (or in a

¹⁴The true map of the code is always what you get by calling **track**.

mathematical article), we could decide to distinguish these structures by using a different “plus” sign depending on the structure: $+$ if complex numbers and say a \oplus if they are vectors.

If the object in FPP is extremely important, the solution in FPP is to define a new type and keep the $+$, $*$, \dots signs for this new type. Therefore we do not allow the concatenation of **probe_8** even when it is reasonable. Instead we construct a map, type **c_damap** described in §??, only if this construction is meaningful. FPP does not prevent the construction of meaningless Taylor maps. The **c_damap** of PTC will be meaningful if the rules between the **probe_8** and **c_damap** types are religiously¹⁵ observed.

Conversely we define a new operator when the creation of a new type is too cumbersome due to its infrequent usage. We do this on **c_damap** allowing “DA” concatenation and “TPSA” concatenation via a different symbol rather than a different type. This will be explained in §??.

¹⁵Neither FPP, nor PTC nor Bmad prevents a user to do crazy things and shove a **probe_8** into a **c_damap** anyway he sees fit. But beware of the results.

14 Knobs

This type is the most important type if you write a tracking code of respectable length. Imagine that your code tracks in one degree of freedom (1-d-f). Then you will push two phase space variables through your magnets, let us call them $\mathbf{z} = (z_1, z_2)$. These variables will denote the position and the tangent of an angle in our little example. If it is your intention to always extract a Taylor series around a special orbit, then it would suffice to declare as **taylor** only the phase space variables $\mathbf{z} = (z_1, z_2)$ and any temporary variables the code might use during its calculations.

But what if we want to have a Taylor map that also depends upon some parameter or parameters of the lattice. For example, a map can include quadrupole strengths as independent variables in the maps. Such variables are called “**knobs**.” Since this is a user decision, it is best if the code decides at execution time using the type **real_8**. As an example, consider the code **z_why_polymorphism.f90**:

```
program my_small_code_real_8
use polymorphic_complex_taylor
implicit none
type(real_8) :: z(2)
real(dp) :: z0(2) = [0, 0] ! special orbit
type(real_8) :: L, B, K_q, K_s
integer :: nd = 1, no = 2, np = 0, ip
longprint = .false. ! Shorten "call print" output
! nd = number of degrees of freedom
! no = order of Taylor series
! Number of extra variables beyond 2*nd

call alloc(z)
call alloc(L, B, K_q, K_s)
np=0
print *, "Give L and parameter ordinality (0 if not a parameter)"
read(5,*) L%r, ip
np=np+ip
call make_it_knob(L,ip); np=np+ip;
print *, "Give B and parameter ordinality (0 if not a parameter)"
read(5,*) K_q%r, ip
print *, "Give K_q and parameter ordinality (0 if not a parameter)"
read(5,*) K_q%r, ip
call make_it_knob(K_q,ip); np=np+ip;
print *, "Give K_s and parameter ordinality (0 if not a parameter)"
read(5,*) K_s%r, ip
call make_it_knob(K_s,ip); np=np+ip;
print *, "The order of the Taylor series ?"
read(5,*) no

call init(no,nd,np) ! Initializes TPSA

z(1)=z0(1) + dz_8(1) ! <--- Taylor monomial z_1 added
z(2)=z0(2) + dz_8(2) ! <--- Taylor monomial z_2 added
```

```

call track(z)

call print(z)

contains

subroutine track(z)
implicit none
type(real_8) :: z(2)
  z(1)=z(1)+L*z(2)
  z(2)=z(2)-B-K_q*z(1)-K_s*z(1)**2
end subroutine track

end program my_small_code_real_8

```

In this little code, there is one drift of length **L** followed by a multipole kick that contains a dipole of strength **B**, a quadrupole of strength **K_q** and a sextupole of strength **K_s**. We run the code ignoring the parameters:

```

Give L and parameter ordinality (0 if not a parameter)
1 0
Give B and parameter ordinality (0 if not a parameter)
0 0
Give K_q and parameter ordinality (0 if not a parameter)
.1 0
Give K_s and parameter ordinality (0 if not a parameter)
0 0
The order of the Taylor series ?
2

Properties, NO = 2, NV = 2, INA = 20
*****

1 1.0000000000000000 1 0
1 1.0000000000000000 0 1

Properties, NO = 2, NV = 2, INA = 21
*****

1 -0.1000000000000000 1 0
1 0.9000000000000000 0 1

```

This little program produces Taylor series to second order in the phase space variables **z** = (**z**₁, **z**₂) similar to the programs **Transport** and **Marylie**. However, we can now require that the multipole strengths be variables of the Taylor series without recompiling the program. In this example, we make the quadrupole strength the third variable of TPSA: $K_q = 0.1 + dz_3$.

```

Give L and parameter ordinality (0 if not a parameter)
1 0

```

```

Give B and parameter ordinality (0 if not a parameter)
0 0
Give K_q and parameter ordinality (0 if not a parameter)
.1 1
Give K_s and parameter ordinality (0 if not a parameter)
0 0
The order of the Taylor series ?
2

Properties, NO = 2, NV = 3, INA = 22
*****

1 1.0000000000000000 1 0 0
1 1.0000000000000000 0 1 0

Properties, NO = 2, NV = 3, INA = 23
*****

1 -0.1000000000000000 1 0 0
1 0.9000000000000000 0 1 0
2 -1.0000000000000000 1 0 1
2 -1.0000000000000000 0 1 1

```

Again, we must emphasize that while it would have been easy here to use the type **taylor** for all the variables, it is totally unfeasible in a real tracking code to either recompile the code or allow all parameters of the systems to be Taylor series. This is why typical matrix¹⁶ codes, not using TPSA, are limited to a small set of Taylor variables, usually the six phase space variables.

So in summary a **real_8** polymorph can be as mentioned in §8.1:

1. A real number
2. a Taylor series with real coefficients (**taylor**)
3. a knob which is a simple temporary Taylor series activated only if needed

¹⁶This is not true of Berz's COSY INFINITY which handles variable memory of TPSA within its own internal language.

15 Manual To Do List

Note: calling init again wipes out existing Taylor series. (Does it wipe out universal taylor?)

Explain knobs