Lecture 10
Thur. 9.24.2015

Equations of Lagrange and Hamilton mechanics in GeneralizedCurvilinear Coordinates (GCC)

(Ch. 12 of Unit 1 and Ch. 1-5 of Unit 2 and Ch. 1-5 of Unit 3)

Quick Review of Lagrange Relations in Lectures 8-9

Using differential chain-rules for coordinate transformations
- *Polar coordinate example of Generalized Curvilinear Coordinates (GCC)*
- *Getting the GCC ready for mechanics: Generalized velocity and Jacobian Lemma 1*
- *Getting the GCC ready for mechanics: Generalized acceleration and Lemma 2*

How to say Newton's "F=ma" in Generalized Curvilinear Coords.
- *Use Cartesian KE quadratic form* $KE=T=1/2\,\mathbf{v}\bullet\mathbf{M}\bullet\mathbf{v}$ *and* $\mathbf{F}=\mathbf{M}\bullet\mathbf{a}$ *to get GCC force*
- *Lagrange GCC trickery gives Lagrange force equations*
- *Lagrange GCC trickery gives Lagrange potential equations (Lagrange 1 and 2)*

GCC Cells, base vectors, and metric tensors
- *Polar coordinate examples:* Covariant $\mathbf{E}_m$ *vs.* Contravariant $\mathbf{E}^m$
- Covariant g_{mn} *vs.* Invariant δ_m^n *vs.* Contravariant g^{mn}

Lagrange prefers Covariant g_{mn} *with* Contravariant *velocity*
- *GCC Lagrangian definition*
- *GCC "canonical" momentum* p_m *definition*
- *GCC "canonical" force* F_m *definition*
  - *Coriolis "fictitious" forces (... and weather effects)*

Quick Review of Lagrange Relations in Lectures 9-10

→ *0th and 1st equations of Lagrange and Hamilton*

Quick Review of Lagrange Relations in Lectures 9-10

0^{th} and 1^{st} equations of Lagrange and Hamilton

Starts out with simple demands for explicit-dependence, "loyalty" or "fealty to the colors"

Lagrangian** and **Estrangian** have no explicit dependence on **momentum p

$$\frac{\partial L}{\partial p_k} \equiv 0 \equiv \frac{\partial E}{\partial p_k}$$

Hamiltonian** and **Estrangian** have no explicit dependence on **velocity v

$$\frac{\partial H}{\partial v_k} \equiv 0 \equiv \frac{\partial E}{\partial v_k}$$

Lagrangian** and **Hamiltonian** have no explicit dependence on **speedinum V

$$\frac{\partial L}{\partial V_k} \equiv 0 \equiv \frac{\partial H}{\partial V_k}$$

Such non-dependencies hold in spite of "under-the-table" matrix and partial-differential connections

$$\nabla_v L = \frac{\partial L}{\partial \mathbf{v}} = \frac{\partial}{\partial \mathbf{v}} \frac{\mathbf{v}\bullet\mathbf{M}\bullet\mathbf{v}}{2} = \mathbf{M}\bullet\mathbf{v} = \mathbf{p}$$

$$\begin{pmatrix} \frac{\partial L}{\partial v_1} \\ \frac{\partial L}{\partial v_2} \end{pmatrix} = \begin{pmatrix} m_1 & 0 \\ 0 & m_2 \end{pmatrix} \begin{pmatrix} v_1 \\ v_2 \end{pmatrix} = \begin{pmatrix} p_1 \\ p_2 \end{pmatrix}$$

Lagrange's 1^{st} equation(s)

$$\frac{\partial L}{\partial v_k} = p_k \quad \text{or:} \quad \frac{\partial L}{\partial \mathbf{v}} = \mathbf{p}$$

$$\nabla_p H = \mathbf{v} = \frac{\partial H}{\partial \mathbf{p}} = \frac{\partial}{\partial \mathbf{p}} \frac{\mathbf{p}\bullet\mathbf{M}^{-1}\bullet\mathbf{p}}{2} = \mathbf{M}^{-1}\bullet\mathbf{p} = \mathbf{v}$$

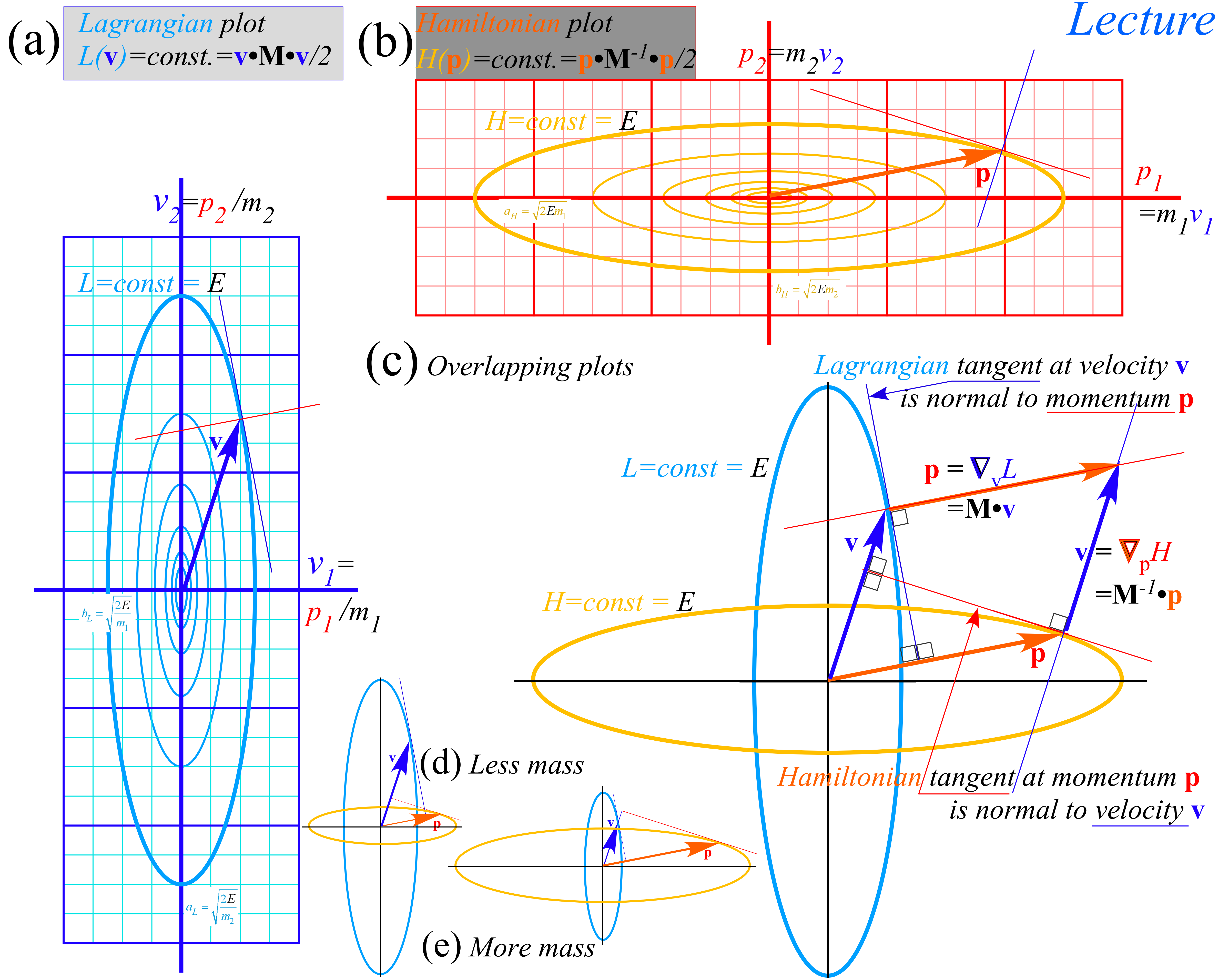
$$\begin{pmatrix} \frac{\partial H}{\partial p_1} \\ \frac{\partial H}{\partial p_2} \end{pmatrix} = \begin{pmatrix} m_1^{-1} & 0 \\ 0 & m_2^{-1} \end{pmatrix} \begin{pmatrix} p_1 \\ p_2 \end{pmatrix} = \begin{pmatrix} v_1 \\ v_2 \end{pmatrix}$$

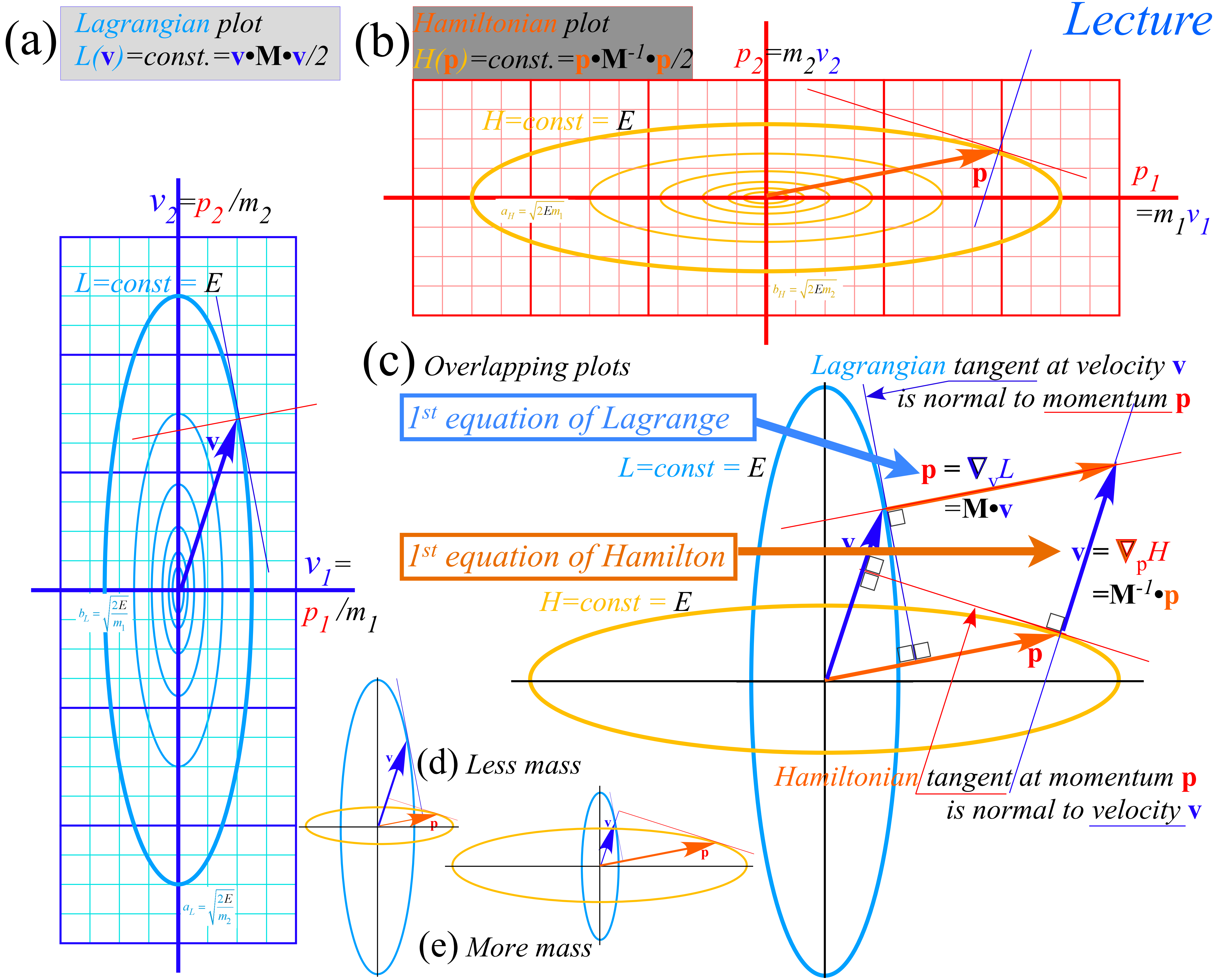
Hamilton's 1^{st} equation(s)

$$\frac{\partial H}{\partial p_k} = v_k \quad \text{or:} \quad \frac{\partial H}{\partial \mathbf{p}} = \mathbf{v}$$

(Forget Estrangian for now)

p. 25 of Lecture 9


(a) Lagrangian plot
L(v)=const.=v•M•v/2
(b) Hamiltonian plot
H(p)=const.=p•M^-1•p/2
p2=m2v2
H=const = E
p
p1
=m1v1
aH = √2Em1
bH = √2Em2
v2=p2/m2
L=const = E
v
v1=
p1/m1
bL = √(2E/m1)
aL = √(2E/m2)
(c) Overlapping plots
Lagrangian tangent at velocity v
is normal to momentum p
L=const = E
p = ∇vL
=M•v
v
v = ∇pH
=M^-1•p
H=const = E
p
Hamiltonian tangent at momentum p
is normal to velocity v
(d) Less mass
(e) More mass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Lagrangian plot
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Hamiltonian plot
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p2=m2v2
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1st equation of Lagrange
L=const = E
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1st equation of Hamilton
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Using differential chain-rules for coordinate transformations

→ *Polar coordinate example of Generalized Curvilinear Coordinates (GCC)*

Getting the GCC ready for mechanics: Generalized velocity and Jacobian Lemma 1

Getting the GCC ready for mechanics: Generalized acceleration and Lemma 2

Using differential chain-rules[†] for coordinate transformations

A pair of 2-variable functions f(x,y) and g(x,y) can define a coordinate system on (x,y)-space

for example: polar coordinates

$$df(x,y) = \frac{\partial f}{\partial x}dx + \frac{\partial f}{\partial y}dy$$

$r^2(x,y) = x^2 + y^2$ *and* $\theta(x,y) = atan2(y,x)$

$$dr(x,y) = \frac{\partial r}{\partial x}dx + \frac{\partial r}{\partial y}dy$$

$$dg(x,y) = \frac{\partial g}{\partial x}dx + \frac{\partial g}{\partial y}dy$$

(Not in text. Recall Lecture 9 p. 15-19)[†]

$$d\theta(x,y) = \frac{\partial \theta}{\partial x}dx + \frac{\partial \theta}{\partial y}dy$$

Using differential chain-rules† for coordinate transformations

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Easy to invert differential chain relations (even if functions are not easily inverted)

$$dx = \frac{\partial x}{\partial f}df + \frac{\partial y}{\partial g}dg$$

$$dy = \frac{\partial y}{\partial f}df + \frac{\partial y}{\partial g}dg$$

$$x = r\cos\theta$$

$$y = r\sin\theta$$

$$dx = \frac{\partial x}{\partial r}dr + \frac{\partial x}{\partial \theta}d\theta$$

$$dy = \frac{\partial y}{\partial r}dr + \frac{\partial y}{\partial \theta}d\theta$$

$$\begin{pmatrix} dx \\ dy \end{pmatrix} = \begin{pmatrix} \frac{\partial x}{\partial r} & \frac{\partial x}{\partial \theta} \\ \frac{\partial y}{\partial r} & \frac{\partial y}{\partial \theta} \end{pmatrix} \begin{pmatrix} dr \\ d\theta \end{pmatrix} = \begin{pmatrix} \cos\theta & -r\sin\theta \\ \sin\theta & r\cos\theta \end{pmatrix} \begin{pmatrix} dr \\ d\theta \end{pmatrix}$$

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$r^2(x,y) = x^2+y^2$ and $\theta(x,y)=atan2(y,x)$

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Notation for differential GCC (Generalized Curvilinear Coordinates $\{q^1, q^2, q^3, ...\}$)

$$dx^j = \frac{\partial x^j}{\partial q^m} dq^m \left(\equiv \sum_{m=1}^{N} \frac{\partial x^j}{\partial q^m} dq^m \quad \left\{ \begin{array}{l} \text{Defining a shorthand} \\ \text{dummy-index } m\text{-sum} \end{array} \right\} \right)$$

What does "q" stand for?
One guess: "*Queer*"
And they do get pretty queer!

These x^j are plain old CC (Cartesian Coordinates $\{dx^1=dx,\ dx^2=dy,\ dx^3=dx,\ dx^4=dt\}$)

Using differential chain-rules† for coordinate transformations

A pair of 2-variable functions f(x,y) and g(x,y) can define a coordinate system on (x,y)-space

$$df(x,y) = \frac{\partial f}{\partial x}dx + \frac{\partial f}{\partial y}dy$$

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What does "*q*" stand for?
One guess: "*Queer*"
And they do get pretty queer!

Connection lines may help to indicate summation (OK on scratch paper...Difficult in text)

These x^j are plain old CC (Cartesian Coordinates $\{dx^1=dx,\ dx^2=dy,\ dx^3=dx,\ dx^4=dt\}$)

Using differential chain-rules for coordinate transformations

Polar coordinate example of Generalized Curvilinear Coordinates (GCC)

→ *Getting the GCC ready for mechanics: Generalized velocity and Jacobian Lemma 1*

Getting the GCC ready for mechanics: Generalized acceleration and Lemma 2

Getting the GCC ready for mechanics:

Generalized velocity relation follows from GCC chain rule

$$dx^j = \frac{\partial x^j}{\partial q^m} dq^m$$

Same kind of linear relation exists between CC velocity $v^j \equiv \dot{x}^j \equiv \frac{dx^j}{dt}$ and GCC velocity $\upsilon^m \equiv \dot{q}^m \equiv \frac{dq^m}{dt}$

$$\dot{x}^j = \frac{\partial x^j}{\partial q^m} \dot{q}^m$$

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This is a key "lemma-1" for setting up mechanics:

$$\dot{x}^j = \frac{\partial x^j}{\partial q^m} \dot{q}^m$$

or:

$$\frac{\partial \dot{x}^j}{\partial \dot{q}^m} = \frac{\partial x^j}{\partial q^m}$$

lemma-1

Getting the GCC ready for mechanics:

Generalized velocity relation follows from GCC chain rule $dx^j = \frac{\partial x^j}{\partial q^m} dq^m$

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Jacobian J_m^j matrix gives each CCC differential dx^j or velocity $\dot{x}^j$ in terms of GCC dq^m or $\dot{q}^m$.

$$J_m^j \equiv \frac{\partial x^j}{\partial q^m} = \frac{\partial \dot{x}^j}{\partial \dot{q}^m} \quad \left\{\begin{matrix}\text{Defining Jacobian} \\ \text{matrix component}\end{matrix}\right\}$$

Recall polar coordinate transformation matrix:

$$\begin{pmatrix} \frac{\partial x}{\partial r} & \frac{\partial x}{\partial \theta} \\ \frac{\partial y}{\partial r} & \frac{\partial y}{\partial \theta} \end{pmatrix} = \begin{pmatrix} \cos\theta & -r\sin\theta \\ \sin\theta & r\cos\theta \end{pmatrix}$$

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$$J_m^j \equiv \frac{\partial x^j}{\partial q^m} = \frac{\partial \dot{x}^j}{\partial \dot{q}^m}$$ {Defining *Jacobian* matrix component}

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Inverse (so-called) *Kajobian* K_j^m matrix is flipped partial derivatives of J_m^j.

$$K_j^m \equiv \frac{\partial q^m}{\partial x^j} = \frac{\partial \dot{q}^m}{\partial \dot{x}^j}$$ {Defining *"Kajobian"* (inverse to Jacobian)}

Polar coordinate inverse transformation matrix:

$$\begin{pmatrix} \frac{\partial x}{\partial r} & \frac{\partial x}{\partial \theta} \\ \frac{\partial y}{\partial r} & \frac{\partial y}{\partial \theta} \end{pmatrix}^{-1} = \begin{pmatrix} \frac{\partial r}{\partial x} & \frac{\partial r}{\partial y} \\ \frac{\partial \theta}{\partial x} & \frac{\partial \theta}{\partial y} \end{pmatrix} = \frac{\begin{pmatrix} r\cos\theta & r\sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}}{(\det J = r)} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\frac{\sin\theta}{r} & \frac{\cos\theta}{r} \end{pmatrix}$$

Defining 2x2 matrix inverse: *(always test inverse matrices!)*

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix}^{-1} = \frac{\begin{pmatrix} D & -B \\ -C & A \end{pmatrix}}{AD - BC}$$

Getting the GCC ready for mechanics:

Generalized velocity relation follows from GCC chain rule

$$dx^j = \frac{\partial x^j}{\partial q^m} dq^m$$

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$$K_j^m \equiv \frac{\partial q^m}{\partial x^j} = \frac{\partial \dot{q}^m}{\partial \dot{x}^j} \quad \left\{\begin{array}{l}\text{Defining "Kajobian"} \\ \text{(inverse to Jacobian)}\end{array}\right\}$$

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$$\begin{pmatrix} A & B \\ C & D \end{pmatrix}\begin{pmatrix} D & -B \\ -C & A \end{pmatrix} = \begin{pmatrix} AD-BC & 0 \\ 0 & AD-BC \end{pmatrix}$$

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Product of matrix J_m^j and K_j^m is a unit matrix by definition of partial derivatives.

(always test inverse matrices!)

$$\begin{pmatrix} \cos\theta & -r\sin\theta \\ \sin\theta & r\cos\theta \end{pmatrix} \begin{pmatrix} \cos\theta & \sin\theta \\ -\frac{\sin\theta}{r} & \frac{\cos\theta}{r} \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$

$$K_j^m \cdot J_n^j \equiv \frac{\partial q^m}{\partial x^j} \cdot \frac{\partial x^j}{\partial q^n} = \frac{\partial q^m}{\partial q^n} = \delta_n^m = \begin{cases} 1 & \textit{if } m = n \\ 0 & \textit{if } m \neq n \end{cases}$$

Using differential chain-rules for coordinate transformations

Polar coordinate example of Generalized Curvilinear Coordinates (GCC)

Getting the GCC ready for mechanics: Generalized velocity and Jacobian Lemma 1

→ *Getting the GCC ready for mechanics: Generalized acceleration and Lemma 2*

Getting the GCC ready for mechanics (2nd part)

Generalized acceleration relations are a little more complicated (It's curved coords, after all!)

First apply $\frac{d}{dt}$ to velocity $\dot{x}^j$ and use product rule: $\frac{d}{dt}(u \cdot v) = \frac{du}{dt} \cdot v + u \cdot \frac{dv}{dt}$

$$\ddot{x}^j \equiv \frac{d}{dt}\dot{x}^j = \frac{d}{dt}\left(\frac{\partial x^j}{\partial q^m}\dot{q}^m\right) = \frac{d}{dt}\left(\frac{\partial x^j}{\partial q^m}\right)\dot{q}^m + \frac{\partial x^j}{\partial q^m}\ddot{q}^m$$

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Apply derivative chain sum to Jacobian.

$$\frac{d}{dt}\left(\frac{\partial x^j}{\partial q^m}\right) = \frac{\partial}{\partial q^n}\left(\frac{\partial x^j}{\partial q^m}\right)\frac{dq^n}{dt} = \left(\frac{\partial^2 x^j}{\partial q^n \partial q^m}\right)\frac{dq^n}{dt}$$

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$$\ddot{x}^j \equiv \frac{d}{dt}\dot{x}^j = \frac{d}{dt}\left(\frac{\partial x^j}{\partial q^m}\dot{q}^m\right) = \frac{d}{dt}\left(\frac{\partial x^j}{\partial q^m}\right)\dot{q}^m + \frac{\partial x^j}{\partial q^m}\ddot{q}^m$$

(Not in text. Recall Lecture 9 p. 15-19)†

Apply derivative chain sum to Jacobian. Partial derivatives are reversible. $\partial_m \partial_n = \partial_n \partial_m$

$$\frac{d}{dt}\left(\frac{\partial x^j}{\partial q^m}\right) = \frac{\partial}{\partial q^n}\left(\frac{\partial x^j}{\partial q^m}\right)\frac{dq^n}{dt} = \left(\frac{\partial^2 x^j}{\partial q^n \partial q^m}\right)\frac{dq^n}{dt} = \left(\frac{\partial^2 x^j}{\partial q^m \partial q^n}\right)\frac{dq^n}{dt} = \frac{\partial}{\partial q^m}\left(\frac{\partial x^j}{\partial q^n}\frac{dq^n}{dt}\right)$$

Getting the GCC ready for mechanics (2nd part)

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By chain-rule def. of CC velocity:

$$= \frac{\partial}{\partial q^m}\left(\dot{x}^j\right)$$

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This is the key "lemma-2" for setting up Lagrangian mechanics .

$$\frac{d}{dt}\left(\frac{\partial x^j}{\partial q^m}\right) = \frac{\partial \dot{x}^j}{\partial q^m} \quad \textit{lemma 2}$$

Getting the GCC ready for mechanics (2nd part)

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First apply $\frac{d}{dt}$ to velocity $\dot{x}^j$ and use product rule: $\frac{d}{dt}(u \cdot v) = \frac{du}{dt} \cdot v + u \cdot \frac{dv}{dt}$

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By chain-rule def. of CC velocity:

$$= \frac{\partial}{\partial q^m}\left(\dot{x}^j\right)$$

The "lemma-1" was in the GCC velocity analysis just before this one for acceleration.

$$\frac{\partial \dot{x}^j}{\partial \dot{q}^m} = \frac{\partial x^j}{\partial q^m} \quad \textit{lemma 1}$$

This is the key "lemma-2" for setting up Lagrangian mechanics .

$$\frac{d}{dt}\left(\frac{\partial x^j}{\partial q^m}\right) = \frac{\partial \dot{x}^j}{\partial q^m} \quad \textit{lemma 2}$$

How to say Newton's "F=ma" in Generalized Curvilinear Coords.

→ *Use Cartesian KE quadratic form* $KE=T=1/2\mathbf{v}\bullet\mathbf{M}\bullet\mathbf{v}$ *and* $\mathbf{F}=\mathbf{M}\bullet\mathbf{a}$ *to get GCC force*

Lagrange GCC trickery gives Lagrange force equations

Lagrange GCC trickery gives Lagrange potential equations (Lagrange 1 and 2)

Deriving GCC mechanics from Cartesian Coord. (CC) Newton I-II

Start with stuff we know...(sort of)

Multidimensional CC version of kinetic energy $\frac{1}{2}\mathbf{v}\bullet\mathbf{M}\bullet\mathbf{v}$

$$T=\frac{1}{2}M_{jk}\,v^j v^k=\frac{1}{2}M_{jk}\,\dot{x}^j\dot{x}^k$$

where: M_{jk} are CC inertia <u>constants</u>

Multidimensional CC version of Newt-II (**F**=**M•a**) using M_{jk} *constants*

$$f_j=M_{jk}\,a^k=M_{jk}\,\ddot{x}^k$$

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$$f_j = M_{jk} a^k = M_{jk} \ddot{x}^k$$

Multidimensional CC version of work-energy differential (dW= **F**•d**x**). *Insert GCC differentials* dq^m

$$dW = f_j dx^j = f_j \left(\frac{\partial x^j}{\partial q^m} dq^m \right) = M_{jk} \ddot{x}^k \left(\frac{\partial x^j}{\partial q^m} dq^m \right)$$

(It's time to bring in the queer q^m *!)*

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dq^m are independent so dq^m-sum is true term-by-term. (Still holds if all dq^m are zero but one.)

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Here *generalized GCC force component F_m* is defined:

$$\text{where:} \quad F_m = f_j \frac{\partial x^j}{\partial q^m} = M_{jk}\, \ddot{x}^k \frac{\partial x^j}{\partial q^m}$$

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→ *Lagrange GCC trickery gives Lagrange force equations*

Lagrange GCC trickery gives Lagrange potential equations (Lagrange 1 and 2)

Now Lagrange GCC trickery begins

Obvious stuff...(sort of, if you've looked at it for a century!)

Lagrange's clever end game: First set $A = M_{jk}\ddot{x}^k$ and $B = \frac{\partial x^j}{\partial q^m}$ with calc. formula: $\left[\ddot{A}B = \frac{d}{dt}\left(\dot{A}B\right) - \dot{A}\dot{B}\right]$

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Cartesian M_{jk} *must be constant for this to work*

(Bye, Bye relativistic mechanics or QM!)

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Then convert ∂x^j to $\partial \dot{x}^j$ by *Lemma 1* and *Lemma 2* on 2nd term.

$$F_m = \frac{d}{dt}\left(M_{jk}\dot{x}^k \frac{\partial \dot{x}^j}{\partial \dot{q}^m}\right) - M_{jk}\dot{x}^k \left(\frac{\partial \dot{x}^j}{\partial q^m}\right)$$

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Simplify using: $\left[M_{ij} v^i \frac{\partial v^j}{\partial q} = M_{ij} \frac{\partial}{\partial q} \frac{v^i v^j}{2}\right]$ where q may be $\dot{q}^m$ or q^m

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$\ddot{A}B$ $\quad (\dot{A}B) \quad \dot{A}\dot{B}$

$$F_m = f_j\frac{\partial x^j}{\partial q^m} = M_{jk}\ddot{x}^k\frac{\partial x^j}{\partial q^m} = \frac{d}{dt}\left(M_{jk}\dot{x}^k\frac{\partial x^j}{\partial q^m}\right) - M_{jk}\dot{x}^k\frac{d}{dt}\left(\frac{\partial x^j}{\partial q^m}\right)$$

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The result is *Lagrange's GCC force equation* in terms of *kinetic energy* $T = \frac{1}{2}M_{jk}\dot{x}^j\dot{x}^k$

$$\boxed{F_m = \frac{d}{dt}\frac{\partial T}{\partial \dot{q}^m} - \frac{\partial T}{\partial q^m}}$$

or: $\mathbf{F} = \frac{d}{dt}\frac{\partial T}{\partial \mathbf{v}} - \frac{\partial T}{\partial \mathbf{r}}$

How to say Newton's "F=ma" in Generalized Curvilinear Coords.

Use Cartesian KE quadratic form $KE=T=1/2\,\mathbf{v}\bullet\mathbf{M}\bullet\mathbf{v}$ *and* $\mathbf{F}=\mathbf{M}\bullet\mathbf{a}$ *to get GCC force*

Lagrange GCC trickery gives Lagrange force equations

→ *Lagrange GCC trickery gives Lagrange potential equations (Lagrange 1 and 2)*

But, Lagrange GCC trickery is not yet done...

(Still another trick-up-the-sleeve!)

If the force is conservative it's a gradient $\mathbf{F} = -\nabla U$ In GCC: $F_m = -\frac{\partial U}{\partial q^m}$

$$F_m = -\frac{\partial U}{\partial q^m} = \frac{d}{dt}\frac{\partial T}{\partial \dot{q}^m} - \frac{\partial T}{\partial q^m}$$

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If the force is conservative it's a gradient $\mathbf{F} = -\nabla U$ In GCC: $F_m = -\frac{\partial U}{\partial q^m}$

$$F_m = -\frac{\partial U}{\partial q^m} = \frac{d}{dt}\frac{\partial T}{\partial \dot{q}^m} - \frac{\partial T}{\partial q^m}$$

Becomes *Lagrange's GCC potential equation* with a new definition for the *Lagrangian: L=T-U*.

$$0 = \frac{d}{dt}\frac{\partial L}{\partial \dot{q}^m} - \frac{\partial L}{\partial q^m} \qquad L(\dot{q}^m, q^m) = T(\dot{q}^m, q^m) - U(q^m)$$

This trick requires: $\frac{\partial U}{\partial \dot{q}^m} \equiv 0$ *U(r) has <u>NO</u> explicit velocity dependence!*

But, Lagrange GCC trickery is not yet done...

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If the force is conservative it's a gradient $\mathbf{F} = -\nabla U$ In GCC: $F_m = -\frac{\partial U}{\partial q^m}$

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This trick requires: $\frac{\partial U}{\partial \dot{q}^m} \equiv 0$ *U(r) has NO explicit velocity dependence!*

Lagrange's 1st GCC equation (Defining GCC momentum)

$$p_m = \frac{\partial L}{\partial \dot{q}^m}$$

$$\frac{d}{dt}\frac{\partial L}{\partial \dot{q}^m} = \frac{\partial L}{\partial q^m}$$

Recall : $\mathbf{p} = \frac{\partial L}{\partial \mathbf{v}}$

Lagrange's 2nd GCC equation (Change of GCC momentum)

$$\frac{dp_m}{dt} \equiv \dot{p}_m = \frac{\partial L}{\partial q^m}$$

GCC Cells, base vectors, and metric tensors

→ *Polar coordinate examples:* Covariant $\mathbf{E}_m$ *vs.* Contravariant $\mathbf{E}^m$

Covariant g_{mn} *vs.* Invariant δ_m^n *vs.* Contravariant g^{mn}

A dual set of *quasi-unit vectors* show up in Jacobian J and Kajobian K.

J-Columns are *covariant vectors* $\{\mathbf{E}_1=\mathbf{E}_r\ \ \mathbf{E}_2=\mathbf{E}_\phi\}$ K-Rows are *contravariant vectors* $\{\mathbf{E}^1=\mathbf{E}^r\ \ \mathbf{E}^2=\mathbf{E}^\phi\}$

$$\langle J\rangle = \begin{pmatrix} \frac{\partial x^1}{\partial q^1} & \frac{\partial x^1}{\partial q^2} \\ \frac{\partial x^2}{\partial q^1} & \frac{\partial x^2}{\partial q^2} \end{pmatrix} = \begin{pmatrix} \frac{\partial x}{\partial r}=\cos\phi & \frac{\partial x}{\partial \phi}=-r\sin\phi \\ \frac{\partial y}{\partial r}=\sin\phi & \frac{\partial y}{\partial \phi}=r\cos\phi \end{pmatrix}$$

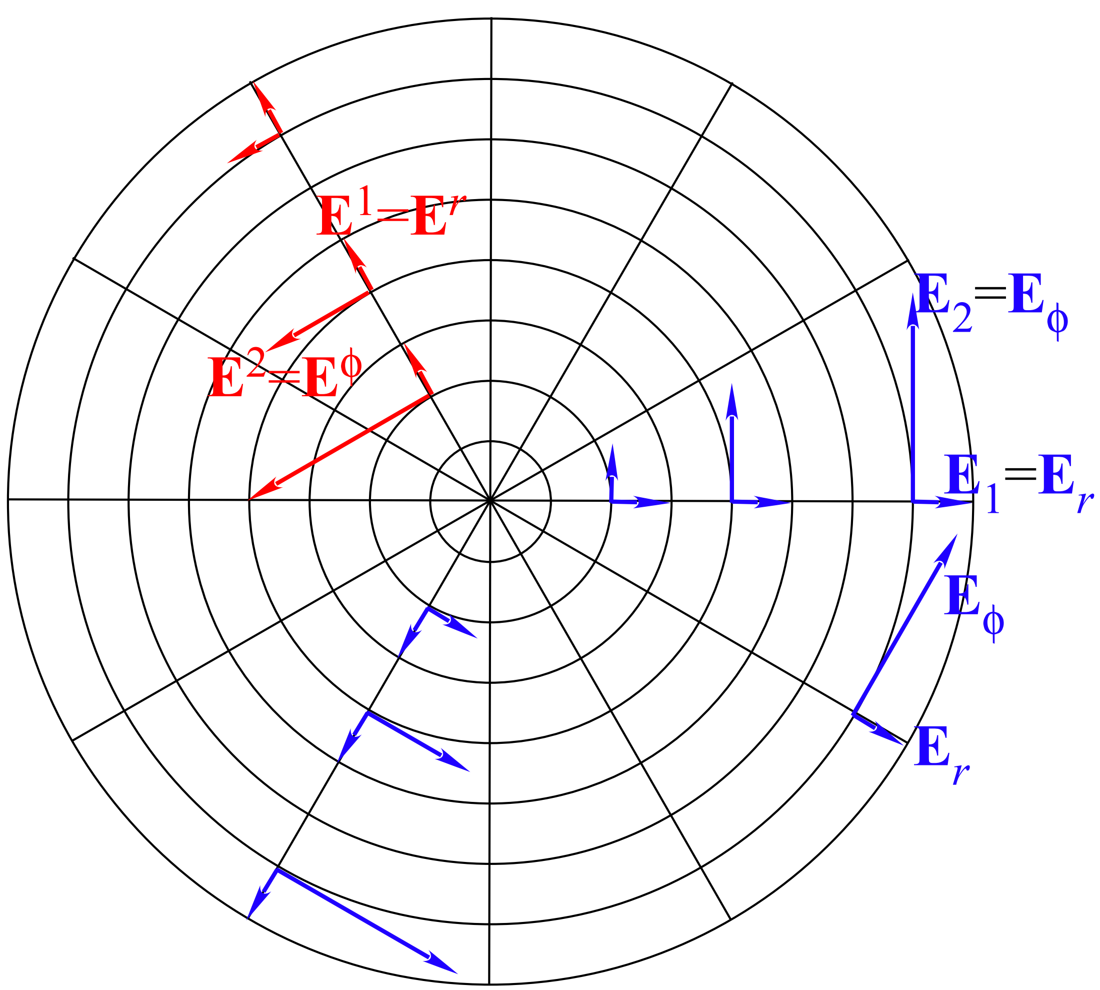
$\uparrow\mathbf{E}_1\ \uparrow\mathbf{E}_2\quad\uparrow\mathbf{E}_r\quad\uparrow\mathbf{E}_\phi$

$$\langle K\rangle = \langle J^{-1}\rangle = \begin{pmatrix} \frac{\partial r}{\partial x}=\cos\phi & \frac{\partial r}{\partial y}=\sin\phi \\ \frac{\partial \phi}{\partial x}=\frac{-\sin\phi}{r} & \frac{\partial \phi}{\partial y}=\frac{\cos\phi}{r} \end{pmatrix} \begin{matrix} \leftarrow \mathbf{E}^r=\mathbf{E}^1 \\ \leftarrow \mathbf{E}^\phi=\mathbf{E}^2 \end{matrix}$$

Derived from polar definition: $x=r\cos\phi$ *and* $y=r\sin\phi$

Inverse polar definition:
$r^2=x^2+y^2$ *and* $\phi=\text{atan2}(y,x)$

(a) Polar coordinate bases



NOTE:These are 2D drawings! No 3D perspective

Unit 1
Fig. 12.10

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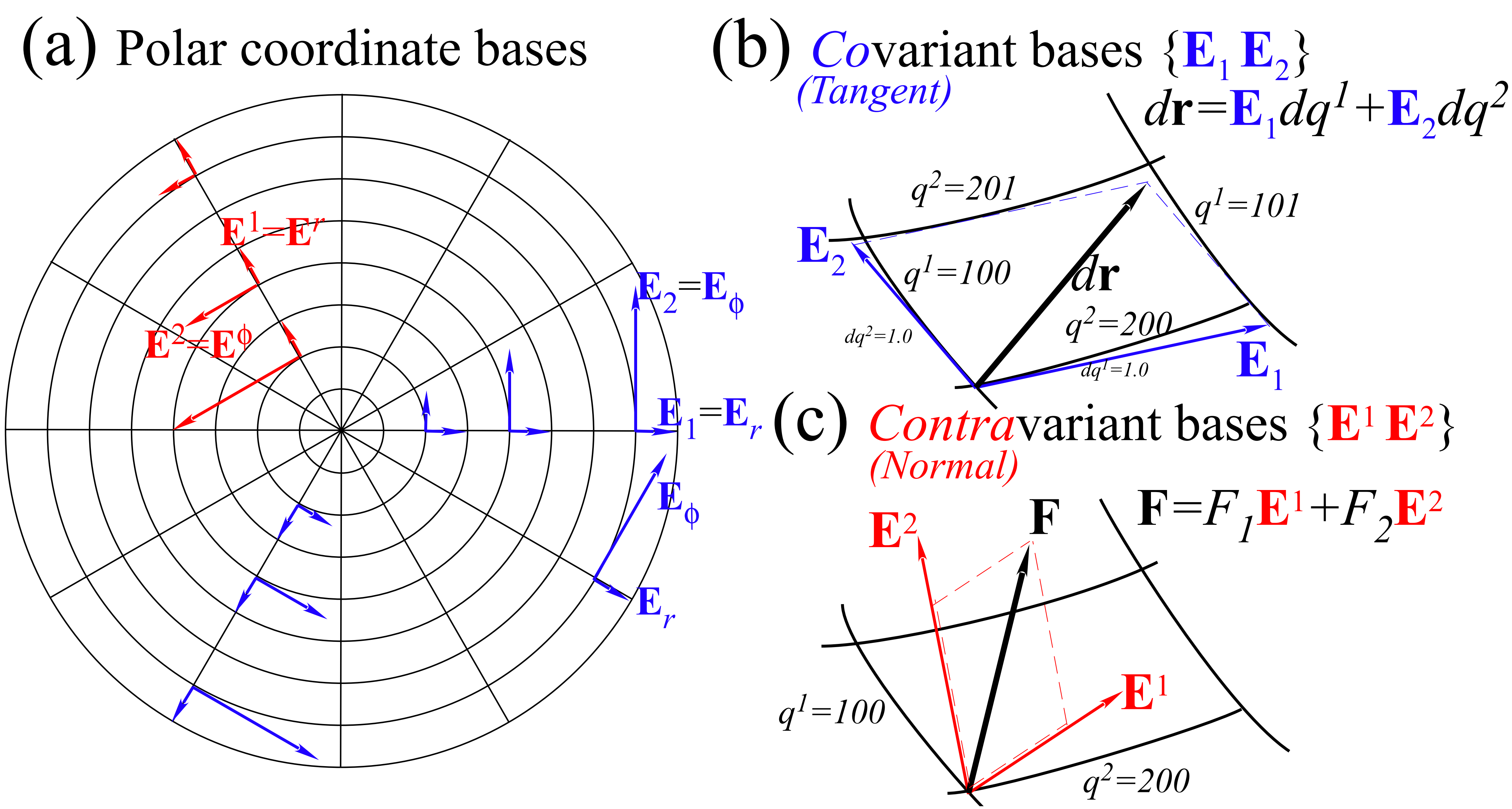
Derived from polar definition: $x=r\cos\phi$ *and* $y=r\sin\phi$

Inverse polar definition:

$r^2=x^2+y^2$ *and* $\phi=\text{atan2}(y,x)$



NOTE:These are 2D drawings! *No* 3D *perspective*

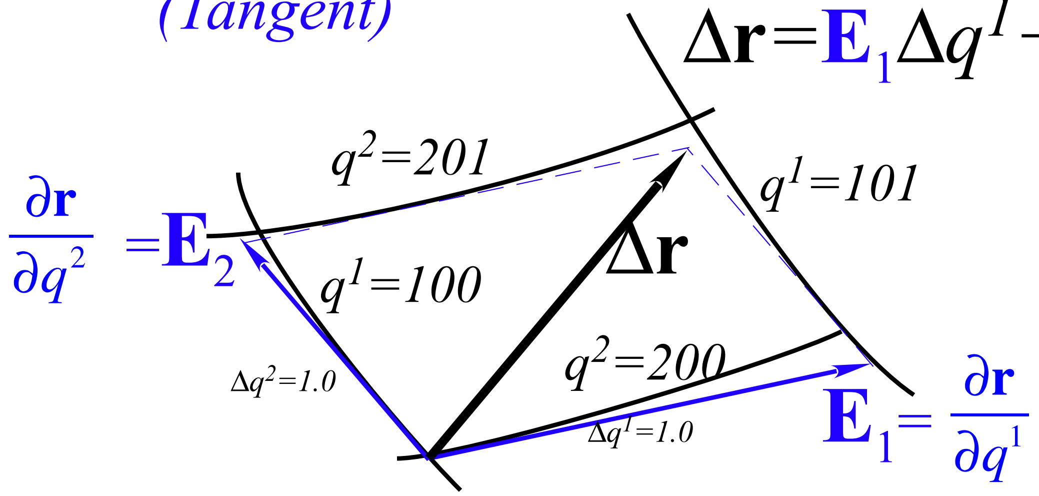
Unit 1
Fig. 12.10

Comparison: Covariant $\mathbf{E}_m = \frac{\partial \mathbf{r}}{\partial q^m}$ *vs. Contravariant* $\mathbf{E}^m = \frac{\partial q^m}{\partial \mathbf{r}} = \nabla q^m$

geometric unit

*Co*variant bases $\{\mathbf{E}_1\ \mathbf{E}_2\}$ match cell walls
(Tangent)

$\Delta\mathbf{r} = \mathbf{E}_1 \Delta q^1 + \mathbf{E}_2 \Delta q^2$ *is based on chain rule:* $d\mathbf{r} = \frac{\partial \mathbf{r}}{\partial q^1} dq^1 + \frac{\partial \mathbf{r}}{\partial q^2} dq^2 = \mathbf{E}_1 dq^1 + \mathbf{E}_2 dq^2$



NOTE:These
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No 3D *perspective*

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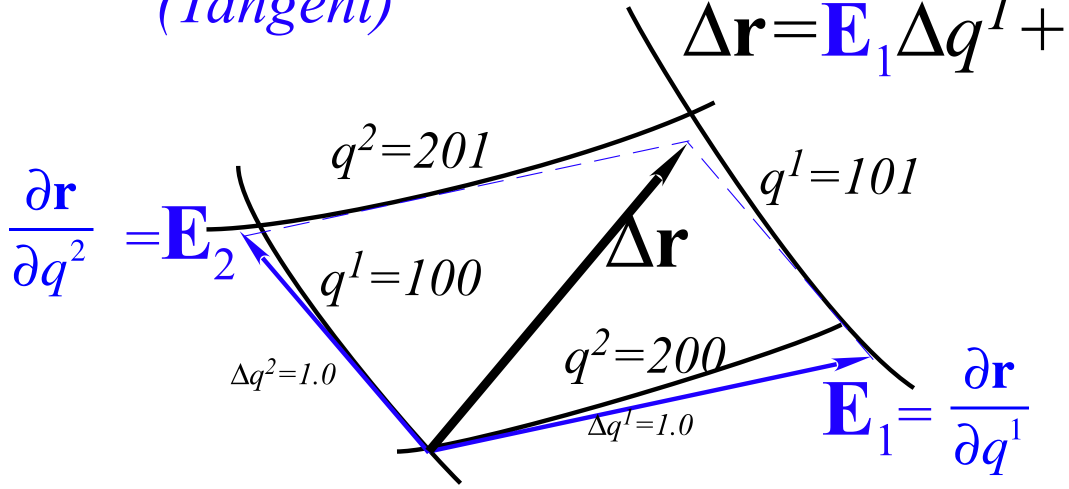

$\mathbf{E}_1$ *follows tangent to* q^2*=const.* ...
since only q^1 *varies in* $\frac{\partial \mathbf{r}}{\partial q^1}$
while q^2, q^3,... *remain constant*

NOTE:These are 2D drawings! *No* 3D *perspective*

Comparison: Covariant $\mathbf{E}_m = \frac{\partial \mathbf{r}}{\partial q^m}$ *vs.* *Contravariant* $\mathbf{E}^m = \frac{\partial q^m}{\partial \mathbf{r}} = \nabla q^m$

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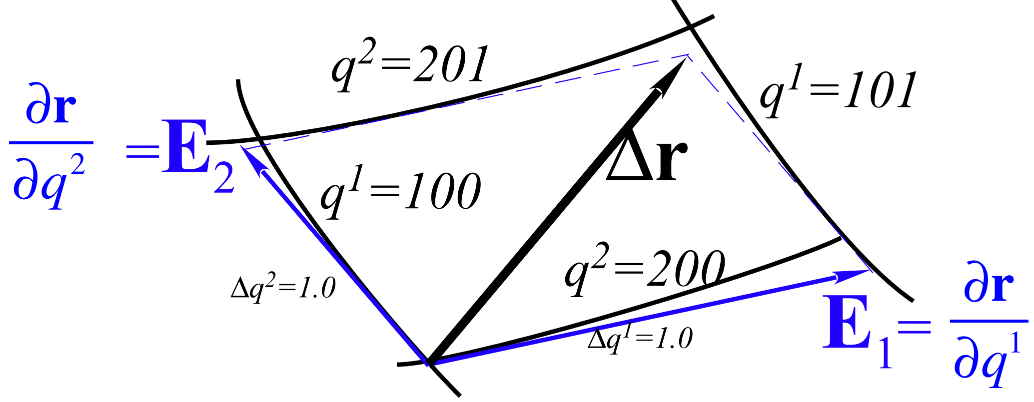

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$\mathbf{E}_m$ are convenient bases for *ex*tensive quantities like distance and velocity.

$$\mathbf{V} = V^1 \mathbf{E}_1 + V^2 \mathbf{E}_2 = V^1 \frac{\partial \mathbf{r}}{\partial q^1} + V^2 \frac{\partial \mathbf{r}}{\partial q^2}$$

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Comparison: Covariant $\mathbf{E}_m = \frac{\partial \mathbf{r}}{\partial q^m}$ *vs.* *Contravariant* $\mathbf{E}^m = \frac{\partial q^m}{\partial \mathbf{r}} = \nabla q^m$

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(Tangent)

$$\Delta \mathbf{r} = \mathbf{E}_1 \Delta q^1 + \mathbf{E}_2 \Delta q^2$$

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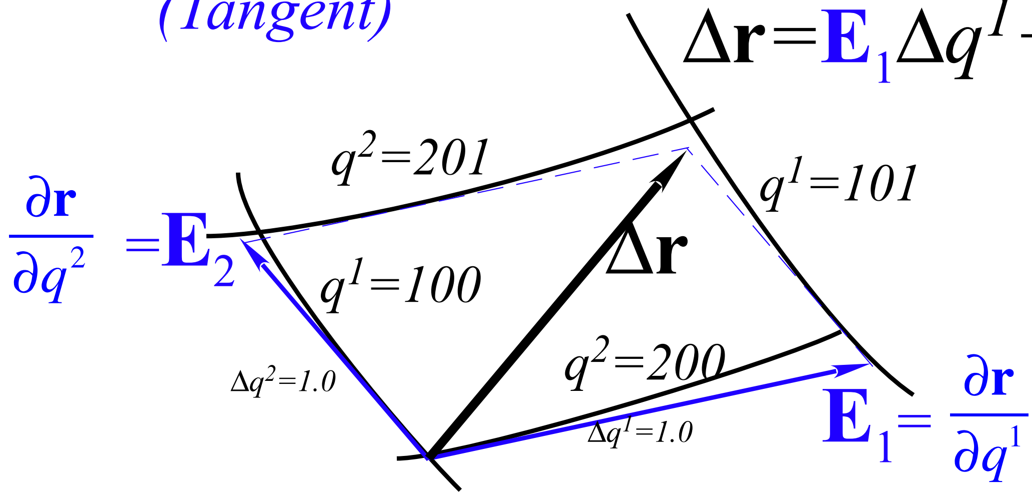

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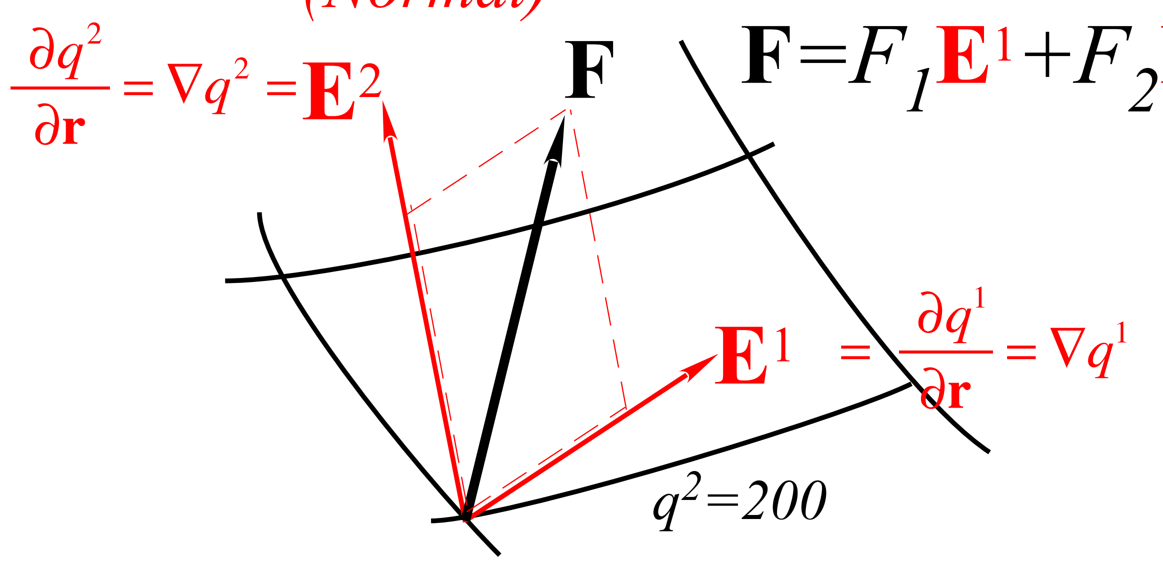
*Contra*variant $\{\mathbf{E}^1\ \mathbf{E}^2\}$ match reciprocal cells

(Normal)

$$\mathbf{F} = F_1 \mathbf{E}^1 + F_2 \mathbf{E}^2$$



NOTE:These
are 2D drawings!
No 3D perspective

$\mathbf{E}^1$ *is normal to* q^1*=const. since*
gradient *of* q^1 *is vector sum* $\nabla q^1 = \begin{pmatrix} \frac{\partial q^1}{\partial x} \\ \frac{\partial q^1}{\partial y} \end{pmatrix}$
of all its partial derivatives

Comparison: Covariant $\mathbf{E}_m = \frac{\partial \mathbf{r}}{\partial q^m}$ *vs. Contravariant* $\mathbf{E}^m = \frac{\partial q^m}{\partial \mathbf{r}} = \nabla q^m$

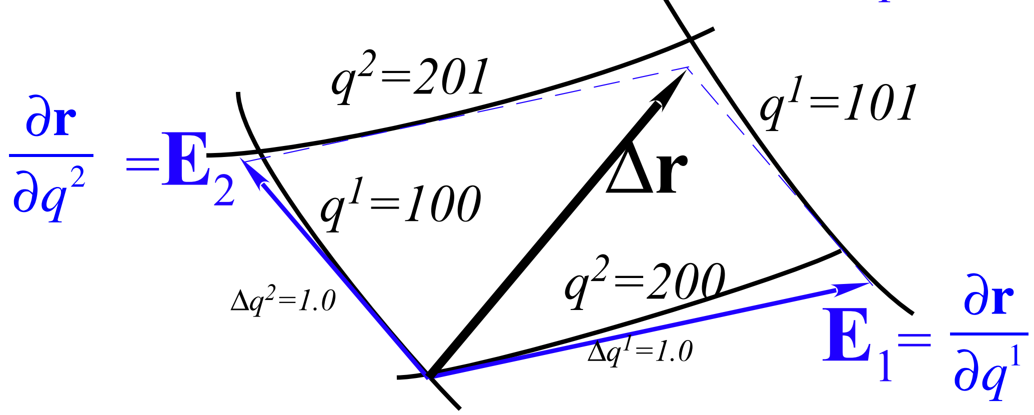
geometric unit

*Co*variant bases $\{\mathbf{E}_1\ \mathbf{E}_2\}$ match cell walls

(Tangent)

$$\Delta\mathbf{r} = \mathbf{E}_1 \Delta q^1 + \mathbf{E}_2 \Delta q^2$$

is based on chain rule: $d\mathbf{r} = \frac{\partial \mathbf{r}}{\partial q^1} dq^1 + \frac{\partial \mathbf{r}}{\partial q^2} dq^2 = \mathbf{E}_1 dq^1 + \mathbf{E}_2 dq^2$



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$$\mathbf{V} = V^1\mathbf{E}_1 + V^2\mathbf{E}_2 = V^1 \frac{\partial \mathbf{r}}{\partial q^1} + V^2 \frac{\partial \mathbf{r}}{\partial q^2}$$

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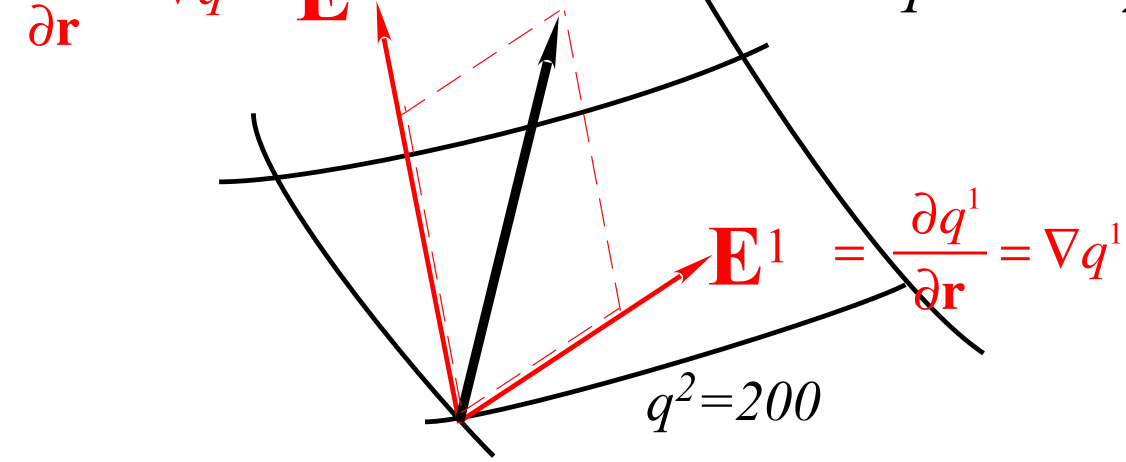
$$\mathbf{F} = F_1\mathbf{E}^1 + F_2\mathbf{E}^2$$



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$\mathbf{E}^m$ are convenient bases for *in*tensive quantities like force and momentum.

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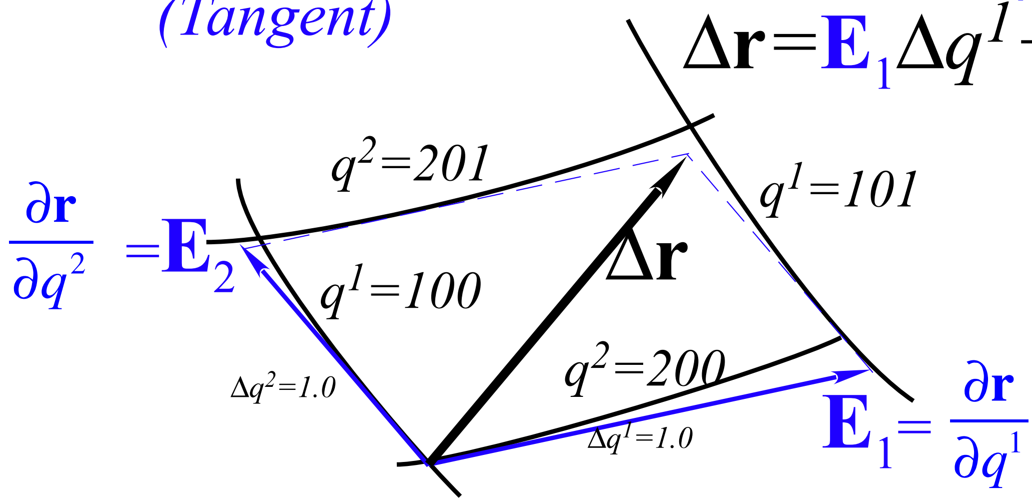
Comparison: Covariant $\mathbf{E}_m = \frac{\partial \mathbf{r}}{\partial q^m}$ vs. Contravariant $\mathbf{E}^n = \frac{\partial q^n}{\partial \mathbf{r}} = \nabla q^n$

Covariant bases $\{\mathbf{E}_1\ \mathbf{E}_2\}$ match cell walls (geometric unit)

(Tangent)

$\Delta\mathbf{r} = \mathbf{E}_1 \Delta q^1 + \mathbf{E}_2 \Delta q^2$

is based on chain rule: $d\mathbf{r} = \frac{\partial \mathbf{r}}{\partial q^1} dq^1 + \frac{\partial \mathbf{r}}{\partial q^2} dq^2 = \mathbf{E}_1 dq^1 + \mathbf{E}_2 dq^2$



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$$\mathbf{V} = V^1\mathbf{E}_1 + V^2\mathbf{E}_2 = V^1\frac{\partial \mathbf{r}}{\partial q^1} + V^2\frac{\partial \mathbf{r}}{\partial q^2}$$

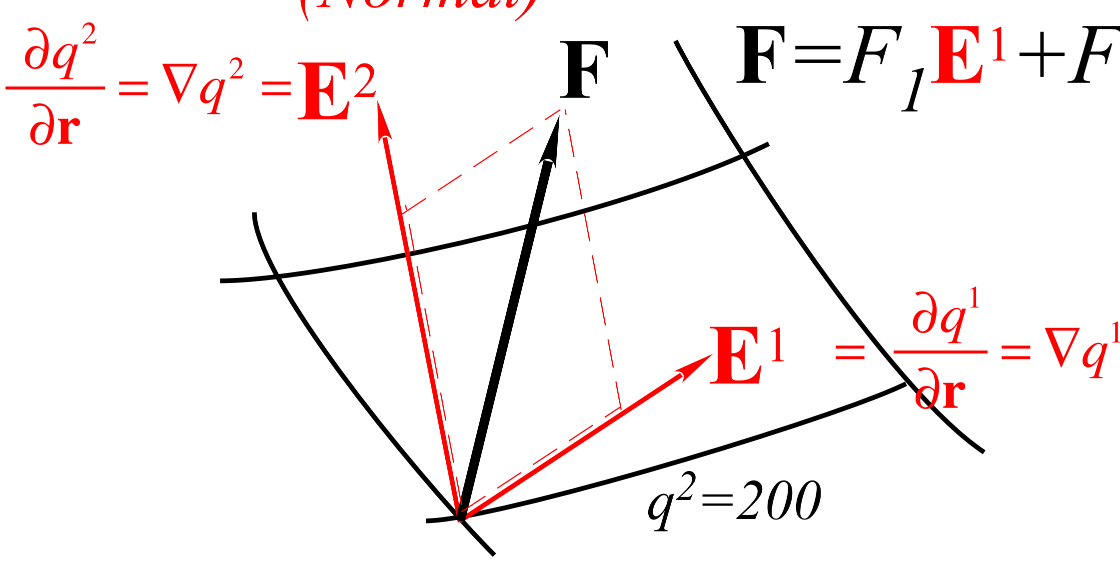
Co-Contra dot products $\mathbf{E}_m \cdot \mathbf{E}^n$ are orthonormal:

$$\mathbf{E}_m \cdot \mathbf{E}^n = \frac{\partial \mathbf{r}}{\partial q^m} \cdot \frac{\partial q^n}{\partial \mathbf{r}} = \delta_m^n$$

Contravariant $\{\mathbf{E}^1\ \mathbf{E}^2\}$ match reciprocal cells

(Normal)

$\mathbf{F} = F_1\mathbf{E}^1 + F_2\mathbf{E}^2$



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GCC Cells, base vectors, and metric tensors

Polar coordinate examples: Covariant $\mathbf{E}_m$ *vs.* Contravariant $\mathbf{E}^m$

→ Covariant g_{mn} *vs.* Invariant $\delta_m{}^n$ *vs.* Contravariant g^{mn}

Covariant g_{mn} vs. Invariant $\delta_m{}^n$ vs. Contravariant g^{mn}

$$\mathbf{E}_m \bullet \mathbf{E}_n = \frac{\partial \mathbf{r}}{\partial q^m} \bullet \frac{\partial \mathbf{r}}{\partial q^n} \equiv g_{mn}$$

$$\mathbf{E}_m \bullet \mathbf{E}^n = \frac{\partial \mathbf{r}}{\partial q^m} \bullet \frac{\partial q^n}{\partial \mathbf{r}} = \delta_m^n$$

$$\mathbf{E}^m \bullet \mathbf{E}^n = \frac{\partial q^m}{\partial \mathbf{r}} \bullet \frac{\partial q^n}{\partial \mathbf{r}} \equiv g^{mn}$$

Covariant
metric tensor
g_{mn}

Invariant
Kroneker unit tensor

$$\delta_m^n \equiv \begin{cases} 1 & \text{if } m = n \\ 0 & \text{if } m \neq n \end{cases}$$

Contravariant
metric tensor
g^{mn}

Covariant g_{mn} vs. Invariant $\delta_m^{\ n}$ vs. Contravariant g^{mn}

$$\mathbf{E}_m \bullet \mathbf{E}_n = \frac{\partial \mathbf{r}}{\partial q^m} \bullet \frac{\partial \mathbf{r}}{\partial q^n} \equiv g_{mn}$$

$$\mathbf{E}_m \bullet \mathbf{E}^n = \frac{\partial \mathbf{r}}{\partial q^m} \bullet \frac{\partial q^n}{\partial \mathbf{r}} = \delta_m^n$$

$$\mathbf{E}^m \bullet \mathbf{E}^n = \frac{\partial q^m}{\partial \mathbf{r}} \bullet \frac{\partial q^n}{\partial \mathbf{r}} \equiv g^{mn}$$

Covariant metric tensor g_{mn}

Invariant Kroneker unit tensor

$$\delta_m^n \equiv \begin{cases} 1 & \text{if } m = n \\ 0 & \text{if } m \neq n \end{cases}$$

Contravariant metric tensor g^{mn}

Polar coordinate examples (again):

$$\langle J \rangle = \begin{pmatrix} \frac{\partial x^1}{\partial q^1} & \frac{\partial x^1}{\partial q^2} \\ \frac{\partial x^2}{\partial q^1} & \frac{\partial x^2}{\partial q^2} \end{pmatrix} = \begin{pmatrix} \frac{\partial x}{\partial r} = \cos\phi & \frac{\partial x}{\partial \phi} = -r\sin\phi \\ \frac{\partial y}{\partial r} = \sin\phi & \frac{\partial y}{\partial \phi} = r\cos\phi \end{pmatrix}$$

$$\uparrow \mathbf{E}_1 \quad \uparrow \mathbf{E}_2 \qquad \uparrow \mathbf{E}_r \quad \uparrow \mathbf{E}_\phi$$

$$\langle K \rangle = \langle J^{-1} \rangle = \begin{pmatrix} \frac{\partial r}{\partial x} = \cos\phi & \frac{\partial r}{\partial y} = \sin\phi \\ \frac{\partial \phi}{\partial x} = \frac{-\sin\phi}{r} & \frac{\partial \phi}{\partial y} = \frac{\cos\phi}{r} \end{pmatrix} \begin{matrix} \leftarrow \mathbf{E}^r = \mathbf{E}^1 \\ \leftarrow \mathbf{E}^\phi = \mathbf{E}^2 \end{matrix}$$

Covariant g_{mn} vs. Invariant δ_m^n vs. Contravariant g^{mn}

$$\mathbf{E}_m \bullet \mathbf{E}_n = \frac{\partial \mathbf{r}}{\partial q^m} \bullet \frac{\partial \mathbf{r}}{\partial q^n} \equiv g_{mn}$$

$$\mathbf{E}_m \bullet \mathbf{E}^n = \frac{\partial \mathbf{r}}{\partial q^m} \bullet \frac{\partial q^n}{\partial \mathbf{r}} = \delta_m^n$$

$$\mathbf{E}^m \bullet \mathbf{E}^n = \frac{\partial q^m}{\partial \mathbf{r}} \bullet \frac{\partial q^n}{\partial \mathbf{r}} \equiv g^{mn}$$

Covariant metric tensor g_{mn}

Invariant Kroneker unit tensor

$$\delta_m^n \equiv \begin{cases} 1 & \text{if } m = n \\ 0 & \text{if } m \neq n \end{cases}$$

Contravariant metric tensor g^{mn}

Polar coordinate examples (again):

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$\uparrow \mathbf{E}_1 \quad \uparrow \mathbf{E}_2 \qquad \uparrow \mathbf{E}_r \qquad \uparrow \mathbf{E}_\phi$

$$\langle K \rangle = \langle J^{-1} \rangle = \begin{pmatrix} \frac{\partial r}{\partial x} = \cos\phi & \frac{\partial r}{\partial y} = \sin\phi \\ \frac{\partial \phi}{\partial x} = \frac{-\sin\phi}{r} & \frac{\partial \phi}{\partial y} = \frac{\cos\phi}{r} \end{pmatrix} \begin{matrix} \leftarrow \mathbf{E}^r = \mathbf{E}^1 \\ \leftarrow \mathbf{E}^\phi = \mathbf{E}^2 \end{matrix}$$

Covariant g_{mn}

$$\begin{pmatrix} g_{rr} & g_{r\phi} \\ g_{\phi r} & g_{\phi\phi} \end{pmatrix} = \begin{pmatrix} \mathbf{E}_r \bullet \mathbf{E}_r & \mathbf{E}_r \bullet \mathbf{E}_\phi \\ \mathbf{E}_\phi \bullet \mathbf{E}_r & \mathbf{E}_\phi \bullet \mathbf{E}_\phi \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 0 & r^2 \end{pmatrix}$$

Invariant δ_m^n

$$\begin{pmatrix} \delta_r^r & \delta_r^\phi \\ \delta_\phi^r & \delta_\phi^\phi \end{pmatrix} = \begin{pmatrix} \mathbf{E}_r \bullet \mathbf{E}^r & \mathbf{E}_r \bullet \mathbf{E}^\phi \\ \mathbf{E}_\phi \bullet \mathbf{E}^r & \mathbf{E}_\phi \bullet \mathbf{E}^\phi \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$

Contravariant g^{mn}

$$\begin{pmatrix} g^{rr} & g^{r\phi} \\ g^{\phi r} & g^{\phi\phi} \end{pmatrix} = \begin{pmatrix} \mathbf{E}^r \bullet \mathbf{E}^r & \mathbf{E}^r \bullet \mathbf{E}^\phi \\ \mathbf{E}^\phi \bullet \mathbf{E}^r & \mathbf{E}^\phi \bullet \mathbf{E}^\phi \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 0 & 1/r^2 \end{pmatrix}$$

Lagrange prefers Co*variant* g_{mn} *with* Contra*variant* *velocity* $\dot{q}^m$

→ *GCC Lagrangian definition*

GCC "canonical" momentum p_m *definition*

GCC "canonical" force F_m *definition*

Coriolis "fictitious" forces (... and weather effects)

Lagrange prefers Covariant g_{mn} with Contravariant velocity

Lagrangian L=KE-U is supposed to be explicit function of velocity.

$$L(\mathbf{v}) = \frac{1}{2}M\mathbf{v}\bullet\mathbf{v} - U = \frac{1}{2}M\dot{\mathbf{r}}\bullet\dot{\mathbf{r}} - U = \frac{1}{2}M(\mathbf{E}_m\dot{q}^m)\bullet(\mathbf{E}_n\dot{q}^n) - U = \frac{1}{2}M(g_{mn}\dot{q}^m\dot{q}^n) - U = L(\dot{q})$$

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Use polar coordinate Covariant g_{mn} metric (page 53)

$$\begin{pmatrix} g_{rr} & g_{r\phi} \\ g_{\phi r} & g_{\phi\phi} \end{pmatrix} = \begin{pmatrix} \mathbf{E}_r \bullet \mathbf{E}_r & \mathbf{E}_r \bullet \mathbf{E}_\phi \\ \mathbf{E}_\phi \bullet \mathbf{E}_r & \mathbf{E}_\phi \bullet \mathbf{E}_\phi \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 0 & r^2 \end{pmatrix}$$

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Use polar coordinate Covariant g_{mn} metric (page 53)

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This gives polar GCC form (Actually it's an OCC or Orthogonal Curvilinear Coordinate form)

$$L(\dot{r},\dot{\phi}) = \tfrac{1}{2}M(g_{rr}\dot{r}^2 + g_{\phi\phi}\dot{\phi}^2) - U(r,\phi) = \tfrac{1}{2}M(1\cdot\dot{r}^2 + r^2\cdot\dot{\phi}^2) - U(r,\phi)$$

Lagrange prefers <u>Co</u>*variant* g_{mn} *with* <u>Contra</u>*variant velocity* $\dot{q}^m$

GCC Lagrangian definition

→ *GCC "canonical" momentum* p_m *definition*

GCC "canonical" force F_m *definition*

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Use polar coordinate Covariant g_{mn} metric (page 53)

$$\begin{pmatrix} g_{rr} & g_{r\phi} \\ g_{\phi r} & g_{\phi\phi} \end{pmatrix} = \begin{pmatrix} \mathbf{E}_r\bullet\mathbf{E}_r & \mathbf{E}_r\bullet\mathbf{E}_\phi \\ \mathbf{E}_\phi\bullet\mathbf{E}_r & \mathbf{E}_\phi\bullet\mathbf{E}_\phi \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 0 & r^2 \end{pmatrix}$$

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(From preceding page)

Lagrange prefers Covariant g_{mn} with Contravariant velocity

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$$L(\mathbf{v}) = \tfrac{1}{2}M\mathbf{v}\bullet\mathbf{v} - U = \tfrac{1}{2}M\dot{\mathbf{r}}\bullet\dot{\mathbf{r}} - U = \tfrac{1}{2}M(\mathbf{E}_m\dot{q}^m)\bullet(\mathbf{E}_n\dot{q}^n) - U = \tfrac{1}{2}M(g_{mn}\dot{q}^m\dot{q}^n) - U = L(\dot{q})$$

Use polar coordinate Covariant g_{mn} metric (page 53)

$$\begin{pmatrix} g_{rr} & g_{r\phi} \\ g_{\phi r} & g_{\phi\phi} \end{pmatrix} = \begin{pmatrix} \mathbf{E}_r\bullet\mathbf{E}_r & \mathbf{E}_r\bullet\mathbf{E}_\phi \\ \mathbf{E}_\phi\bullet\mathbf{E}_r & \mathbf{E}_\phi\bullet\mathbf{E}_\phi \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 0 & r^2 \end{pmatrix}$$

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$$L(\dot{r},\dot{\phi}) = \tfrac{1}{2}M(g_{rr}\dot{r}^2 + g_{\phi\phi}\dot{\phi}^2) - U(r,\phi) = \tfrac{1}{2}M(1\cdot\dot{r}^2 + r^2\cdot\dot{\phi}^2) - U(r,\phi)$$

GCC Lagrange equations follow. 1st L-equation is momentum p_m definition for each coordinate q^m:

$$p_r = \frac{\partial L}{\partial \dot{r}} = M\, g_{rr}\dot{r} = M\,\dot{r}$$

Nothing too surprising;
radial momentum p_r has the
usual linear $M\cdot v$ form

Lagrange prefers Covariant g_{mn} with Contravariant velocity

Lagrangian KE-U is supposed to be explicit function of velocity.

$$L(\mathbf{v}) = \tfrac{1}{2}M\mathbf{v}\bullet\mathbf{v} - U = \tfrac{1}{2}M\dot{\mathbf{r}}\bullet\dot{\mathbf{r}} - U = \tfrac{1}{2}M(\mathbf{E}_m\dot{q}^m)\bullet(\mathbf{E}_n\dot{q}^n) - U = \tfrac{1}{2}M(g_{mn}\dot{q}^m\dot{q}^n) - U = L(\dot{q})$$

Use polar coordinate Covariant g_{mn} metric (page 53)

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Torque relates to two distinct parts: Coriolis and angular acceleration

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Rewriting GCC Lagrange equations :

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Conventional forms

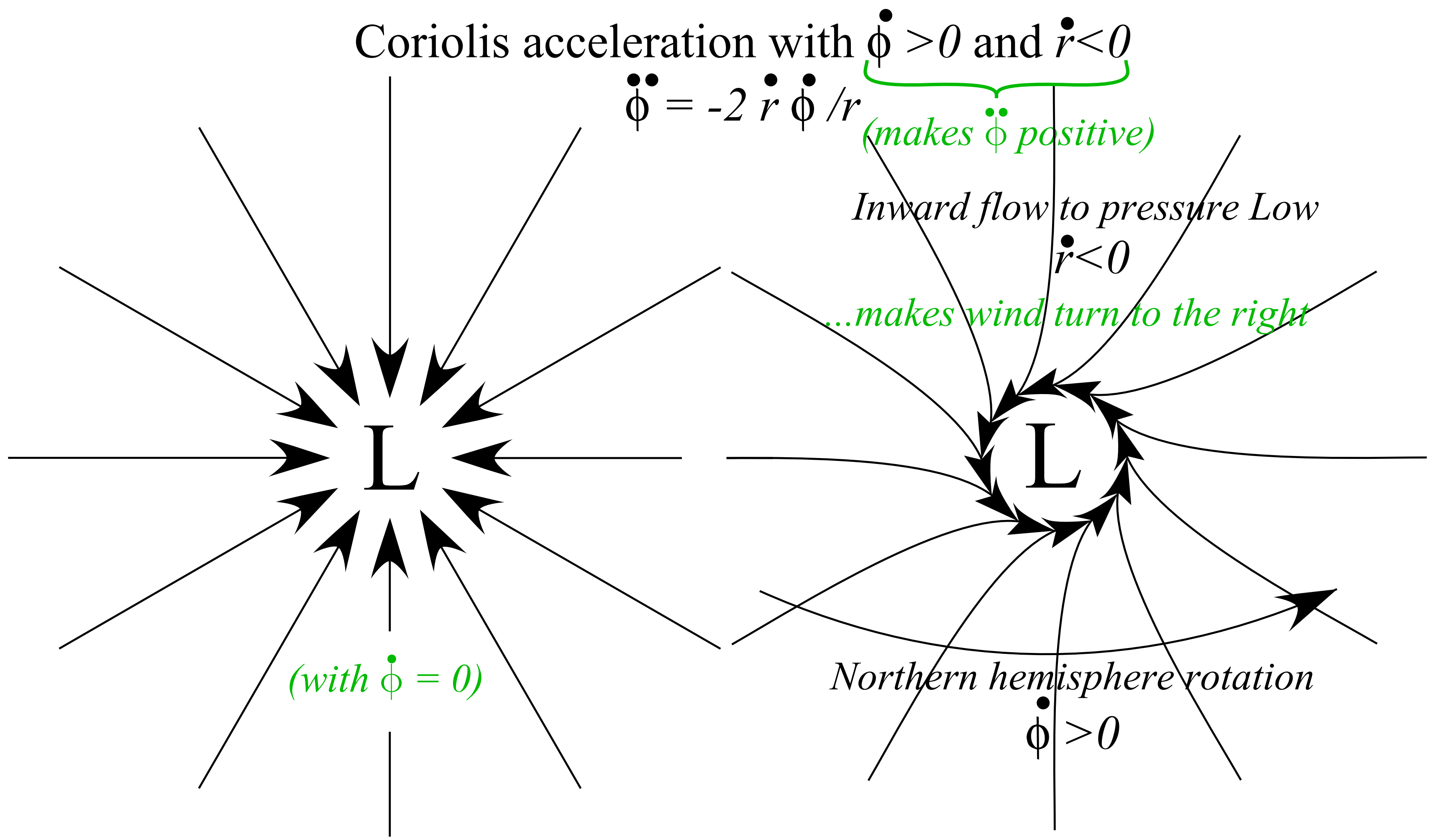
radial force: $M\ddot{r} = M r\dot{\phi}^2 - \frac{\partial U}{\partial r}$

angular force or torque: $Mr^2\ddot{\phi} = -2Mr\dot{r}\dot{\phi} - \frac{\partial U}{\partial \phi}$

Field-free (U=0)

radial acceleration: $\ddot{r} = r\dot{\phi}^2$

angular acceleration: $\ddot{\phi} = -2\frac{\dot{r}\dot{\phi}}{r}$



Effect on Northern Hemisphere local weather

Cyclonic flow around lows

Lecture 10 ends here
Thur. 9.24.2015