# MA 229/MA 235 - Lecture 27 

IISc

- Definition of integration of


## Recap

- Definition of integration of compactly supported smooth forms


## Recap

- Definition of integration of compactly supported smooth forms over oriented smooth manifolds (with or without boundary), and


## Recap

- Definition of integration of compactly supported smooth forms over oriented smooth manifolds (with or without boundary), and its properties.
- Definition of integration of compactly supported smooth forms over oriented smooth manifolds (with or without boundary), and its properties.
- Saw that


## Recap

- Definition of integration of compactly supported smooth forms over oriented smooth manifolds (with or without boundary), and its properties.
- Saw that even integrating $x^{2} d x \wedge d y$ over $\bar{D}$ is a tricky affair.


## Practically speaking...

## Practically speaking...

- To relate these two,


## Practically speaking...

- To relate these two, here is a proposition:


## Practically speaking...

- To relate these two, here is a proposition: Let $\omega$ be a compactly supported top form on $M$.


## Practically speaking...

- To relate these two, here is a proposition: Let $\omega$ be a compactly supported top form on $M$. Let $D_{1}, \ldots, D_{k}$ be domains of integration in $\mathbb{R}^{n}$ and


## Practically speaking...

- To relate these two, here is a proposition: Let $\omega$ be a compactly supported top form on $M$. Let $D_{1}, \ldots, D_{k}$ be domains of integration in $\mathbb{R}^{n}$ and $F_{i}: \bar{D}_{i} \rightarrow M$ be smooth maps


## Practically speaking...

- To relate these two, here is a proposition: Let $\omega$ be a compactly supported top form on $M$. Let $D_{1}, \ldots, D_{k}$ be domains of integration in $\mathbb{R}^{n}$ and $F_{i}: \bar{D}_{i} \rightarrow M$ be smooth maps that restrict to orientation-preserving diffeos on $D_{i}$,


## Practically speaking...

- To relate these two, here is a proposition: Let $\omega$ be a compactly supported top form on $M$. Let $D_{1}, \ldots, D_{k}$ be domains of integration in $\mathbb{R}^{n}$ and $F_{i}: \bar{D}_{i} \rightarrow M$ be smooth maps that restrict to orientation-preserving diffeos on $D_{i}$, $F\left(D_{i}\right) \cap F\left(D_{j}\right)=\phi$,


## Practically speaking...

- To relate these two, here is a proposition: Let $\omega$ be a compactly supported top form on $M$. Let $D_{1}, \ldots, D_{k}$ be domains of integration in $\mathbb{R}^{n}$ and $F_{i}: \bar{D}_{i} \rightarrow M$ be smooth maps that restrict to orientation-preserving diffeos on $D_{i}$, $F\left(D_{i}\right) \cap F\left(D_{j}\right)=\phi, \operatorname{supp}(\omega) \subset F\left(\bar{D}_{1}\right) \cup F\left(\bar{D}_{2}\right) \ldots$
- To relate these two, here is a proposition: Let $\omega$ be a compactly supported top form on $M$. Let $D_{1}, \ldots, D_{k}$ be domains of integration in $\mathbb{R}^{n}$ and $F_{i}: \bar{D}_{i} \rightarrow M$ be smooth maps that restrict to orientation-preserving diffeos on $D_{i}$, $F\left(D_{i}\right) \cap F\left(D_{j}\right)=\phi, \operatorname{supp}(\omega) \subset F\left(\bar{D}_{1}\right) \cup F\left(\bar{D}_{2}\right) \ldots$ Then $\int_{M} \omega=\sum_{i} \int_{D_{i}} F_{i}^{*} \omega$.


## Practically speaking...

## Practically speaking...

- Before proving it,


## Practically speaking...

- Before proving it, note that the identity map


## Practically speaking...

- Before proving it, note that the identity map does the trick for $D \subset \mathbb{R}^{2}$ above.


## Practically speaking...

- Before proving it, note that the identity map does the trick for $D \subset \mathbb{R}^{2}$ above. Thus $\int_{D} \omega=\int_{x^{2}+y^{2}<1} x^{2} d x d y$.


## Practically speaking...

- Before proving it, note that the identity map does the trick for $D \subset \mathbb{R}^{2}$ above. Thus $\int_{D} \omega=\int_{x^{2}+y^{2}<1} x^{2} d x d y$.
- Proof:


## Practically speaking...

- Before proving it, note that the identity map does the trick for $D \subset \mathbb{R}^{2}$ above. Thus $\int_{D} \omega=\int_{x^{2}+y^{2}<1} x^{2} d x d y$.
- Proof:As above,


## Practically speaking...

- Before proving it, note that the identity map does the trick for $D \subset \mathbb{R}^{2}$ above. Thus $\int_{D} \omega=\int_{x^{2}+y^{2}<1} x^{2} d x d y$.
- Proof:As above, assume WLOG that $\omega$ is supported in a


## Practically speaking...

- Before proving it, note that the identity map does the trick for $D \subset \mathbb{R}^{2}$ above. Thus $\int_{D} \omega=\int_{x^{2}+y^{2}<1} x^{2} d x d y$.
- Proof:As above, assume WLOG that $\omega$ is supported in a single relatively compact chart $(U, \phi)$.
- Before proving it, note that the identity map does the trick for $D \subset \mathbb{R}^{2}$ above. Thus $\int_{D} \omega=\int_{x^{2}+y^{2}<1} x^{2} d x d y$.
- Proof:As above, assume WLOG that $\omega$ is supported in a single relatively compact chart $(U, \phi)$. Note that $\partial\left(U \cap F_{i}\left(D_{i}\right)\right) \subset F_{i}\left(\partial D_{i}\right)$ (why?)
- Before proving it, note that the identity map does the trick for $D \subset \mathbb{R}^{2}$ above. Thus $\int_{D} \omega=\int_{x^{2}+y^{2}<1} x^{2} d x d y$.
- Proof:As above, assume WLOG that $\omega$ is supported in a single relatively compact chart $(U, \phi)$. Note that $\partial\left(U \cap F_{i}\left(D_{i}\right)\right) \subset F_{i}\left(\partial D_{i}\right)\left(\right.$ why? ) and hence $\phi\left(\partial\left(U \cap F_{i}\left(D_{i}\right)\right)\right)$ has measure zero in $\mathbb{R}^{n}$ :
- Before proving it, note that the identity map does the trick for $D \subset \mathbb{R}^{2}$ above. Thus $\int_{D} \omega=\int_{x^{2}+y^{2}<1} x^{2} d x d y$.
- Proof:As above, assume WLOG that $\omega$ is supported in a single relatively compact chart $(U, \phi)$. Note that $\partial\left(U \cap F_{i}\left(D_{i}\right)\right) \subset F_{i}\left(\partial D_{i}\right)\left(\right.$ why? ) and hence $\phi\left(\partial\left(U \cap F_{i}\left(D_{i}\right)\right)\right)$ has measure zero in $\mathbb{R}^{n}$ : Indeed, smooth maps between $\mathbb{R}^{n}$ and itself take measure zero sets to measure zero sets (why?).
- Before proving it, note that the identity map does the trick for $D \subset \mathbb{R}^{2}$ above. Thus $\int_{D} \omega=\int_{x^{2}+y^{2}<1} x^{2} d x d y$.
- Proof:As above, assume WLOG that $\omega$ is supported in a single relatively compact chart $(U, \phi)$. Note that $\partial\left(U \cap F_{i}\left(D_{i}\right)\right) \subset F_{i}\left(\partial D_{i}\right)\left(\right.$ why? ) and hence $\phi\left(\partial\left(U \cap F_{i}\left(D_{i}\right)\right)\right)$ has measure zero in $\mathbb{R}^{n}$ : Indeed, smooth maps between $\mathbb{R}^{n}$ and itself take measure zero sets to measure zero sets (why?). Moreover, $\phi\left(U \cap F_{i}\left(D_{i}\right)\right)$ cover
- Before proving it, note that the identity map does the trick for $D \subset \mathbb{R}^{2}$ above. Thus $\int_{D} \omega=\int_{x^{2}+y^{2}<1} x^{2} d x d y$.
- Proof:As above, assume WLOG that $\omega$ is supported in a single relatively compact chart $(U, \phi)$. Note that $\partial\left(U \cap F_{i}\left(D_{i}\right)\right) \subset F_{i}\left(\partial D_{i}\right)\left(\right.$ why? ) and hence $\phi\left(\partial\left(U \cap F_{i}\left(D_{i}\right)\right)\right)$ has measure zero in $\mathbb{R}^{n}$ : Indeed, smooth maps between $\mathbb{R}^{n}$ and itself take measure zero sets to measure zero sets (why?). Moreover, $\phi\left(U \cap F_{i}\left(D_{i}\right)\right)$ cover $\phi(\operatorname{supp}(\omega))$ upto measure zero sets
- Before proving it, note that the identity map does the trick for $D \subset \mathbb{R}^{2}$ above. Thus $\int_{D} \omega=\int_{x^{2}+y^{2}<1} x^{2} d x d y$.
- Proof:As above, assume WLOG that $\omega$ is supported in a single relatively compact chart $(U, \phi)$. Note that $\partial\left(U \cap F_{i}\left(D_{i}\right)\right) \subset F_{i}\left(\partial D_{i}\right)\left(\right.$ why? ) and hence $\phi\left(\partial\left(U \cap F_{i}\left(D_{i}\right)\right)\right)$ has measure zero in $\mathbb{R}^{n}$ : Indeed, smooth maps between $\mathbb{R}^{n}$ and itself take measure zero sets to measure zero sets (why?). Moreover, $\phi\left(U \cap F_{i}\left(D_{i}\right)\right)$ cover $\phi(\operatorname{supp}(\omega))$ upto measure zero sets and are pairwise disjoint.
- Before proving it, note that the identity map does the trick for $D \subset \mathbb{R}^{2}$ above. Thus $\int_{D} \omega=\int_{x^{2}+y^{2}<1} x^{2} d x d y$.
- Proof:As above, assume WLOG that $\omega$ is supported in a single relatively compact chart $(U, \phi)$. Note that $\partial\left(U \cap F_{i}\left(D_{i}\right)\right) \subset F_{i}\left(\partial D_{i}\right)\left(\right.$ why? ) and hence $\phi\left(\partial\left(U \cap F_{i}\left(D_{i}\right)\right)\right)$ has measure zero in $\mathbb{R}^{n}$ : Indeed, smooth maps between $\mathbb{R}^{n}$ and itself take measure zero sets to measure zero sets (why?). Moreover, $\phi\left(U \cap F_{i}\left(D_{i}\right)\right)$ cover $\phi(\operatorname{supp}(\omega))$ upto measure zero sets and are pairwise disjoint.
- Thus $\int_{M} \omega= \pm \int_{\phi(U)}\left(\phi^{-1}\right)^{*} \omega= \pm \sum_{i} \int_{\phi\left(U \cap F_{i}\left(D_{i}\right)\right)}\left(\phi^{-1}\right)^{*} \omega=$ $\sum_{i} \int_{D_{i}} F_{i}^{*} \omega$ (why?)
- Before proving it, note that the identity map does the trick for $D \subset \mathbb{R}^{2}$ above. Thus $\int_{D} \omega=\int_{x^{2}+y^{2}<1} x^{2} d x d y$.
- Proof:As above, assume WLOG that $\omega$ is supported in a single relatively compact chart $(U, \phi)$. Note that $\partial\left(U \cap F_{i}\left(D_{i}\right)\right) \subset F_{i}\left(\partial D_{i}\right)\left(\right.$ why? ) and hence $\phi\left(\partial\left(U \cap F_{i}\left(D_{i}\right)\right)\right)$ has measure zero in $\mathbb{R}^{n}$ : Indeed, smooth maps between $\mathbb{R}^{n}$ and itself take measure zero sets to measure zero sets (why?). Moreover, $\phi\left(U \cap F_{i}\left(D_{i}\right)\right)$ cover $\phi(\operatorname{supp}(\omega))$ upto measure zero sets and are pairwise disjoint.
- Thus $\int_{M} \omega= \pm \int_{\phi(U)}\left(\phi^{-1}\right)^{*} \omega= \pm \sum_{i} \int_{\phi\left(U \cap F_{i}\left(D_{i}\right)\right)}\left(\phi^{-1}\right)^{*} \omega=$ $\sum_{i} \int_{D_{i}} F_{i}^{*} \omega$ (why?)
- Actually, one does not need
- Before proving it, note that the identity map does the trick for $D \subset \mathbb{R}^{2}$ above. Thus $\int_{D} \omega=\int_{x^{2}+y^{2}<1} x^{2} d x d y$.
- Proof:As above, assume WLOG that $\omega$ is supported in a single relatively compact chart $(U, \phi)$. Note that $\partial\left(U \cap F_{i}\left(D_{i}\right)\right) \subset F_{i}\left(\partial D_{i}\right)\left(\right.$ why? ) and hence $\phi\left(\partial\left(U \cap F_{i}\left(D_{i}\right)\right)\right)$ has measure zero in $\mathbb{R}^{n}$ : Indeed, smooth maps between $\mathbb{R}^{n}$ and itself take measure zero sets to measure zero sets (why?). Moreover, $\phi\left(U \cap F_{i}\left(D_{i}\right)\right)$ cover $\phi(\operatorname{supp}(\omega))$ upto measure zero sets and are pairwise disjoint.
- Thus $\int_{M} \omega= \pm \int_{\phi(U)}\left(\phi^{-1}\right)^{*} \omega= \pm \sum_{i} \int_{\phi\left(U \cap F_{i}\left(D_{i}\right)\right)}\left(\phi^{-1}\right)^{*} \omega=$ $\sum_{i} \int_{D_{i}} F_{i}^{*} \omega$ (why?)
- Actually, one does not need $F_{i}$ to extend smoothly to $\bar{D}_{i}$.
- Before proving it, note that the identity map does the trick for $D \subset \mathbb{R}^{2}$ above. Thus $\int_{D} \omega=\int_{x^{2}+y^{2}<1} x^{2} d x d y$.
- Proof:As above, assume WLOG that $\omega$ is supported in a single relatively compact chart $(U, \phi)$. Note that $\partial\left(U \cap F_{i}\left(D_{i}\right)\right) \subset F_{i}\left(\partial D_{i}\right)$ (why?) and hence $\phi\left(\partial\left(U \cap F_{i}\left(D_{i}\right)\right)\right)$ has measure zero in $\mathbb{R}^{n}$ : Indeed, smooth maps between $\mathbb{R}^{n}$ and itself take measure zero sets to measure zero sets (why?). Moreover, $\phi\left(U \cap F_{i}\left(D_{i}\right)\right)$ cover $\phi(\operatorname{supp}(\omega))$ upto measure zero sets and are pairwise disjoint.
- Thus $\int_{M} \omega= \pm \int_{\phi(U)}\left(\phi^{-1}\right)^{*} \omega= \pm \sum_{i} \int_{\phi\left(U \cap F_{i}\left(D_{i}\right)\right)}\left(\phi^{-1}\right)^{*} \omega=$ $\sum_{i} \int_{D_{i}} F_{i}^{*} \omega$ (why?)
- Actually, one does not need $F_{i}$ to extend smoothly to $\bar{D}_{i}$. Lipschitz (or even weaker - Hölder) extensions are enough.


## Stokes' theorem

## Stokes' theorem

- Theorem:


## Stokes' theorem

- Theorem: Let $M$ be a smooth oriented


## Stokes' theorem

- Theorem: Let $M$ be a smooth oriented $n$-manifold-with-boundary (where


## Stokes' theorem

- Theorem: Let $M$ be a smooth oriented $n$-manifold-with-boundary (where the boundary has the induced orientation from outward vector fields).


## Stokes' theorem

- Theorem: Let $M$ be a smooth oriented $n$-manifold-with-boundary (where the boundary has the induced orientation from outward vector fields). Let $\omega$ be a compactly supported $n-1$ form on $M$.


## Stokes' theorem

- Theorem: Let $M$ be a smooth oriented $n$-manifold-with-boundary (where the boundary has the induced orientation from outward vector fields). Let $\omega$ be a compactly supported $n-1$ form on $M$. Then $\int_{M} d \omega=\int_{\partial M} \omega$. (
- Theorem: Let $M$ be a smooth oriented $n$-manifold-with-boundary (where the boundary has the induced orientation from outward vector fields). Let $\omega$ be a compactly supported $n-1$ form on $M$. Then $\int_{M} d \omega=\int_{\partial M} \omega$. (In particular, if $\partial M=\phi$,
- Theorem: Let $M$ be a smooth oriented $n$-manifold-with-boundary (where the boundary has the induced orientation from outward vector fields). Let $\omega$ be a compactly supported $n-1$ form on $M$. Then $\int_{M} d \omega=\int_{\partial M} \omega$. (In particular, if $\partial M=\phi$, then $\int_{M} d \omega=0$.)
- Theorem: Let $M$ be a smooth oriented n-manifold-with-boundary (where the boundary has the induced orientation from outward vector fields). Let $\omega$ be a compactly supported $n-1$ form on $M$. Then $\int_{M} d \omega=\int_{\partial M} \omega$. (In particular, if $\partial M=\phi$, then $\int_{M} d \omega=0$.)
- Before we proceed to the proof,
- Theorem: Let $M$ be a smooth oriented n-manifold-with-boundary (where the boundary has the induced orientation from outward vector fields). Let $\omega$ be a compactly supported $n-1$ form on $M$. Then $\int_{M} d \omega=\int_{\partial M} \omega$. (In particular, if $\partial M=\phi$, then $\int_{M} d \omega=0$.)
- Before we proceed to the proof, suppose $M$ is a domain in $\mathbb{R}^{2}$,
- Theorem: Let $M$ be a smooth oriented n-manifold-with-boundary (where the boundary has the induced orientation from outward vector fields). Let $\omega$ be a compactly supported $n-1$ form on $M$. Then $\int_{M} d \omega=\int_{\partial M} \omega$. (In particular, if $\partial M=\phi$, then $\int_{M} d \omega=0$.)
- Before we proceed to the proof, suppose $M$ is a domain in $\mathbb{R}^{2}$, and $\omega=P d x+Q d y$,
- Theorem: Let $M$ be a smooth oriented n-manifold-with-boundary (where the boundary has the induced orientation from outward vector fields). Let $\omega$ be a compactly supported $n-1$ form on $M$. Then $\int_{M} d \omega=\int_{\partial M} \omega$. (In particular, if $\partial M=\phi$, then $\int_{M} d \omega=0$.)
- Before we proceed to the proof, suppose $M$ is a domain in $\mathbb{R}^{2}$, and $\omega=P d x+Q d y$, then $\int_{M} d \omega=\int_{M}\left(\frac{\partial Q}{\partial x}-\frac{\partial P}{\partial y}\right) d V$ and
- Theorem: Let $M$ be a smooth oriented n-manifold-with-boundary (where the boundary has the induced orientation from outward vector fields). Let $\omega$ be a compactly supported $n-1$ form on $M$. Then $\int_{M} d \omega=\int_{\partial M} \omega$. (In particular, if $\partial M=\phi$, then $\int_{M} d \omega=0$.)
- Before we proceed to the proof, suppose $M$ is a domain in $\mathbb{R}^{2}$, and $\omega=P d x+Q d y$, then $\int_{M} d \omega=\int_{M}\left(\frac{\partial Q}{\partial x}-\frac{\partial P}{\partial y}\right) d V$ and $\int_{\partial M} \omega=\int_{\partial M}(P d x+Q d y)$.
- Theorem: Let $M$ be a smooth oriented $n$-manifold-with-boundary (where the boundary has the induced orientation from outward vector fields). Let $\omega$ be a compactly supported $n-1$ form on $M$. Then $\int_{M} d \omega=\int_{\partial M} \omega$. (In particular, if $\partial M=\phi$, then $\int_{M} d \omega=0$.)
- Before we proceed to the proof, suppose $M$ is a domain in $\mathbb{R}^{2}$, and $\omega=P d x+Q d y$, then $\int_{M} d \omega=\int_{M}\left(\frac{\partial Q}{\partial x}-\frac{\partial P}{\partial y}\right) d V$ and $\int_{\partial M} \omega=\int_{\partial M}(P d x+Q d y)$. If $\partial M$ can be parametrised
- Theorem: Let $M$ be a smooth oriented $n$-manifold-with-boundary (where the boundary has the induced orientation from outward vector fields). Let $\omega$ be a compactly supported $n-1$ form on $M$. Then $\int_{M} d \omega=\int_{\partial M} \omega$. (In particular, if $\partial M=\phi$, then $\int_{M} d \omega=0$.)
- Before we proceed to the proof, suppose $M$ is a domain in $\mathbb{R}^{2}$, and $\omega=P d x+Q d y$, then $\int_{M} d \omega=\int_{M}\left(\frac{\partial Q}{\partial x}-\frac{\partial P}{\partial y}\right) d V$ and $\int_{\partial M} \omega=\int_{\partial M}(P d x+Q d y)$. If $\partial M$ can be parametrised as $\gamma:[0,1] \rightarrow \partial M$ where $\gamma$ is a smooth simple closed curve
- Theorem: Let $M$ be a smooth oriented $n$-manifold-with-boundary (where the boundary has the induced orientation from outward vector fields). Let $\omega$ be a compactly supported $n-1$ form on $M$. Then $\int_{M} d \omega=\int_{\partial M} \omega$. (In particular, if $\partial M=\phi$, then $\int_{M} d \omega=0$.)
- Before we proceed to the proof, suppose $M$ is a domain in $\mathbb{R}^{2}$, and $\omega=P d x+Q d y$, then $\int_{M} d \omega=\int_{M}\left(\frac{\partial Q}{\partial x}-\frac{\partial P}{\partial y}\right) d V$ and $\int_{\partial M} \omega=\int_{\partial M}(P d x+Q d y)$. If $\partial M$ can be parametrised as $\gamma:[0,1] \rightarrow \partial M$ where $\gamma$ is a smooth simple closed curve such that $\gamma^{\prime} \neq 0$,
- Theorem: Let $M$ be a smooth oriented $n$-manifold-with-boundary (where the boundary has the induced orientation from outward vector fields). Let $\omega$ be a compactly supported $n-1$ form on $M$. Then $\int_{M} d \omega=\int_{\partial M} \omega$. (In particular, if $\partial M=\phi$, then $\int_{M} d \omega=0$.)
- Before we proceed to the proof, suppose $M$ is a domain in $\mathbb{R}^{2}$, and $\omega=P d x+Q d y$, then $\int_{M} d \omega=\int_{M}\left(\frac{\partial Q}{\partial x}-\frac{\partial P}{\partial y}\right) d V$ and $\int_{\partial M} \omega=\int_{\partial M}(P d x+Q d y)$. If $\partial M$ can be parametrised as $\gamma:[0,1] \rightarrow \partial M$ where $\gamma$ is a smooth simple closed curve such that $\gamma^{\prime} \neq 0$, then by the above result,
- Theorem: Let $M$ be a smooth oriented $n$-manifold-with-boundary (where the boundary has the induced orientation from outward vector fields). Let $\omega$ be a compactly supported $n-1$ form on $M$. Then $\int_{M} d \omega=\int_{\partial M} \omega$. (In particular, if $\partial M=\phi$, then $\int_{M} d \omega=0$.)
- Before we proceed to the proof, suppose $M$ is a domain in $\mathbb{R}^{2}$, and $\omega=P d x+Q d y$, then $\int_{M} d \omega=\int_{M}\left(\frac{\partial Q}{\partial x}-\frac{\partial P}{\partial y}\right) d V$ and $\int_{\partial M} \omega=\int_{\partial M}(P d x+Q d y)$. If $\partial M$ can be parametrised as $\gamma:[0,1] \rightarrow \partial M$ where $\gamma$ is a smooth simple closed curve such that $\gamma^{\prime} \neq 0$, then by the above result,

$$
\int_{\partial M} \omega=\int_{(0,1)} \gamma^{*} \omega=\int_{0}^{1}\left(P \frac{d x}{d t}+Q \frac{d y}{d t}\right) d t
$$

- Theorem: Let $M$ be a smooth oriented $n$-manifold-with-boundary (where the boundary has the induced orientation from outward vector fields). Let $\omega$ be a compactly supported $n-1$ form on $M$. Then $\int_{M} d \omega=\int_{\partial M} \omega$. (In particular, if $\partial M=\phi$, then $\int_{M} d \omega=0$.)
- Before we proceed to the proof, suppose $M$ is a domain in $\mathbb{R}^{2}$, and $\omega=P d x+Q d y$, then $\int_{M} d \omega=\int_{M}\left(\frac{\partial Q}{\partial x}-\frac{\partial P}{\partial y}\right) d V$ and $\int_{\partial M} \omega=\int_{\partial M}(P d x+Q d y)$. If $\partial M$ can be parametrised as $\gamma:[0,1] \rightarrow \partial M$ where $\gamma$ is a smooth simple closed curve such that $\gamma^{\prime} \neq 0$, then by the above result, $\int_{\partial M} \omega=\int_{(0,1)} \gamma^{*} \omega=\int_{0}^{1}\left(P \frac{d x}{d t}+Q \frac{d y}{d t}\right) d t$. (A small point:
- Theorem: Let $M$ be a smooth oriented $n$-manifold-with-boundary (where the boundary has the induced orientation from outward vector fields). Let $\omega$ be a compactly supported $n-1$ form on $M$. Then $\int_{M} d \omega=\int_{\partial M} \omega$. (In particular, if $\partial M=\phi$, then $\int_{M} d \omega=0$.)
- Before we proceed to the proof, suppose $M$ is a domain in $\mathbb{R}^{2}$, and $\omega=P d x+Q d y$, then $\int_{M} d \omega=\int_{M}\left(\frac{\partial Q}{\partial x}-\frac{\partial P}{\partial y}\right) d V$ and $\int_{\partial M} \omega=\int_{\partial M}(P d x+Q d y)$. If $\partial M$ can be parametrised as $\gamma:[0,1] \rightarrow \partial M$ where $\gamma$ is a smooth simple closed curve such that $\gamma^{\prime} \neq 0$, then by the above result, $\int_{\partial M} \omega=\int_{(0,1)} \gamma^{*} \omega=\int_{0}^{1}\left(P \frac{d x}{d t}+Q \frac{d y}{d t}\right) d t$. (A small point: the orientation of $\partial M$
- Theorem: Let $M$ be a smooth oriented $n$-manifold-with-boundary (where the boundary has the induced orientation from outward vector fields). Let $\omega$ be a compactly supported $n-1$ form on $M$. Then $\int_{M} d \omega=\int_{\partial M} \omega$. (In particular, if $\partial M=\phi$, then $\int_{M} d \omega=0$.)
- Before we proceed to the proof, suppose $M$ is a domain in $\mathbb{R}^{2}$, and $\omega=P d x+Q d y$, then $\int_{M} d \omega=\int_{M}\left(\frac{\partial Q}{\partial x}-\frac{\partial P}{\partial y}\right) d V$ and $\int_{\partial M} \omega=\int_{\partial M}(P d x+Q d y)$. If $\partial M$ can be parametrised as $\gamma:[0,1] \rightarrow \partial M$ where $\gamma$ is a smooth simple closed curve such that $\gamma^{\prime} \neq 0$, then by the above result, $\int_{\partial M} \omega=\int_{(0,1)} \gamma^{*} \omega=\int_{0}^{1}\left(P \frac{d x}{d t}+Q \frac{d y}{d t}\right) d t$. (A small point: the orientation of $\partial M$ corresponds to travelling anticlockwise (why?))
- Theorem: Let $M$ be a smooth oriented $n$-manifold-with-boundary (where the boundary has the induced orientation from outward vector fields). Let $\omega$ be a compactly supported $n-1$ form on $M$. Then $\int_{M} d \omega=\int_{\partial M} \omega$. (In particular, if $\partial M=\phi$, then $\int_{M} d \omega=0$.)
- Before we proceed to the proof, suppose $M$ is a domain in $\mathbb{R}^{2}$, and $\omega=P d x+Q d y$, then $\int_{M} d \omega=\int_{M}\left(\frac{\partial Q}{\partial x}-\frac{\partial P}{\partial y}\right) d V$ and $\int_{\partial M} \omega=\int_{\partial M}(P d x+Q d y)$. If $\partial M$ can be parametrised as $\gamma:[0,1] \rightarrow \partial M$ where $\gamma$ is a smooth simple closed curve such that $\gamma^{\prime} \neq 0$, then by the above result, $\int_{\partial M} \omega=\int_{(0,1)} \gamma^{*} \omega=\int_{0}^{1}\left(P \frac{d x}{d t}+Q \frac{d y}{d t}\right) d t$. (A small point: the orientation of $\partial M$ corresponds to travelling anticlockwise (why?)) Thus we have proven Green's theorem. (
- Theorem: Let $M$ be a smooth oriented $n$-manifold-with-boundary (where the boundary has the induced orientation from outward vector fields). Let $\omega$ be a compactly supported $n-1$ form on $M$. Then $\int_{M} d \omega=\int_{\partial M} \omega$. (In particular, if $\partial M=\phi$, then $\int_{M} d \omega=0$.)
- Before we proceed to the proof, suppose $M$ is a domain in $\mathbb{R}^{2}$, and $\omega=P d x+Q d y$, then $\int_{M} d \omega=\int_{M}\left(\frac{\partial Q}{\partial x}-\frac{\partial P}{\partial y}\right) d V$ and $\int_{\partial M} \omega=\int_{\partial M}(P d x+Q d y)$. If $\partial M$ can be parametrised as $\gamma:[0,1] \rightarrow \partial M$ where $\gamma$ is a smooth simple closed curve such that $\gamma^{\prime} \neq 0$, then by the above result, $\int_{\partial M} \omega=\int_{(0,1)} \gamma^{*} \omega=\int_{0}^{1}\left(P \frac{d x}{d t}+Q \frac{d y}{d t}\right) d t$. (A small point: the orientation of $\partial M$ corresponds to travelling anticlockwise (why?)) Thus we have proven Green's theorem. (Extends to the
- Theorem: Let $M$ be a smooth oriented $n$-manifold-with-boundary (where the boundary has the induced orientation from outward vector fields). Let $\omega$ be a compactly supported $n-1$ form on $M$. Then $\int_{M} d \omega=\int_{\partial M} \omega$. (In particular, if $\partial M=\phi$, then $\int_{M} d \omega=0$.)
- Before we proceed to the proof, suppose $M$ is a domain in $\mathbb{R}^{2}$, and $\omega=P d x+Q d y$, then $\int_{M} d \omega=\int_{M}\left(\frac{\partial Q}{\partial x}-\frac{\partial P}{\partial y}\right) d V$ and $\int_{\partial M} \omega=\int_{\partial M}(P d x+Q d y)$. If $\partial M$ can be parametrised as $\gamma:[0,1] \rightarrow \partial M$ where $\gamma$ is a smooth simple closed curve such that $\gamma^{\prime} \neq 0$, then by the above result, $\int_{\partial M} \omega=\int_{(0,1)} \gamma^{*} \omega=\int_{0}^{1}\left(P \frac{d x}{d t}+Q \frac{d y}{d t}\right) d t$. (A small point: the orientation of $\partial M$ corresponds to travelling anticlockwise (why?)) Thus we have proven Green's theorem. (Extends to the multiply connected case.)


## Proof of Stokes' theorem

## Proof of Stokes' theorem

- Cover the support of


## Proof of Stokes' theorem

- Cover the support of $\omega$ by finitely many charts (interior or boundary)


## Proof of Stokes' theorem

- Cover the support of $\omega$ by finitely many charts (interior or boundary) $U_{i}$.
- Cover the support of $\omega$ by finitely many charts (interior or boundary) $U_{i}$. Let $\rho_{i}$ be a partition-of-unity subordinate to this cover.
- Cover the support of $\omega$ by finitely many charts (interior or boundary) $U_{i}$. Let $\rho_{i}$ be a partition-of-unity subordinate to this cover. Then $\int_{M} d \omega=\sum_{i} \int_{M} d\left(\rho_{i} \omega\right)$.
- Cover the support of $\omega$ by finitely many charts (interior or boundary) $U_{i}$. Let $\rho_{i}$ be a partition-of-unity subordinate to this cover. Then $\int_{M} d \omega=\sum_{i} \int_{M} d\left(\rho_{i} \omega\right)$. Thus, if we prove Stokes
- Cover the support of $\omega$ by finitely many charts (interior or boundary) $U_{i}$. Let $\rho_{i}$ be a partition-of-unity subordinate to this cover. Then $\int_{M} d \omega=\sum_{i} \int_{M} d\left(\rho_{i} \omega\right)$. Thus, if we prove Stokes for $\rho_{i} \omega$, i.e.,
- Cover the support of $\omega$ by finitely many charts (interior or boundary) $U_{i}$. Let $\rho_{i}$ be a partition-of-unity subordinate to this cover. Then $\int_{M} d \omega=\sum_{i} \int_{M} d\left(\rho_{i} \omega\right)$. Thus, if we prove Stokes for $\rho_{i} \omega$, i.e., for forms that are
- Cover the support of $\omega$ by finitely many charts (interior or boundary) $U_{i}$. Let $\rho_{i}$ be a partition-of-unity subordinate to this cover. Then $\int_{M} d \omega=\sum_{i} \int_{M} d\left(\rho_{i} \omega\right)$. Thus, if we prove Stokes for $\rho_{i} \omega$, i.e., for forms that are compactly supported in a chart (interior or boundary),
- Cover the support of $\omega$ by finitely many charts (interior or boundary) $U_{i}$. Let $\rho_{i}$ be a partition-of-unity subordinate to this cover. Then $\int_{M} d \omega=\sum_{i} \int_{M} d\left(\rho_{i} \omega\right)$. Thus, if we prove Stokes for $\rho_{i} \omega$, i.e., for forms that are compactly supported in a chart (interior or boundary), then we are done. (why?)
- Cover the support of $\omega$ by finitely many charts (interior or boundary) $U_{i}$. Let $\rho_{i}$ be a partition-of-unity subordinate to this cover. Then $\int_{M} d \omega=\sum_{i} \int_{M} d\left(\rho_{i} \omega\right)$. Thus, if we prove Stokes for $\rho_{i} \omega$, i.e., for forms that are compactly supported in a chart (interior or boundary), then we are done. (why?)
- So assume wlog that
- Cover the support of $\omega$ by finitely many charts (interior or boundary) $U_{i}$. Let $\rho_{i}$ be a partition-of-unity subordinate to this cover. Then $\int_{M} d \omega=\sum_{i} \int_{M} d\left(\rho_{i} \omega\right)$. Thus, if we prove Stokes for $\rho_{i} \omega$, i.e., for forms that are compactly supported in a chart (interior or boundary), then we are done. (why?)
- So assume wlog that $\omega$ is compactly supported in a chart $(U, \phi)$.
- Cover the support of $\omega$ by finitely many charts (interior or boundary) $U_{i}$. Let $\rho_{i}$ be a partition-of-unity subordinate to this cover. Then $\int_{M} d \omega=\sum_{i} \int_{M} d\left(\rho_{i} \omega\right)$. Thus, if we prove Stokes for $\rho_{i} \omega$, i.e., for forms that are compactly supported in a chart (interior or boundary), then we are done. (why?)
- So assume wlog that $\omega$ is compactly supported in a chart $(U, \phi)$. Wlog, $\phi$ is positively oriented (why?)
- Cover the support of $\omega$ by finitely many charts (interior or boundary) $U_{i}$. Let $\rho_{i}$ be a partition-of-unity subordinate to this cover. Then $\int_{M} d \omega=\sum_{i} \int_{M} d\left(\rho_{i} \omega\right)$. Thus, if we prove Stokes for $\rho_{i} \omega$, i.e., for forms that are compactly supported in a chart (interior or boundary), then we are done. (why?)
- So assume wlog that $\omega$ is compactly supported in a chart $(U, \phi)$. Wlog, $\phi$ is positively oriented (why?) Thus $\int_{M} d \omega=\int_{\phi(U)} d\left(\phi^{-1}\right)^{*} \omega$.
- Cover the support of $\omega$ by finitely many charts (interior or boundary) $U_{i}$. Let $\rho_{i}$ be a partition-of-unity subordinate to this cover. Then $\int_{M} d \omega=\sum_{i} \int_{M} d\left(\rho_{i} \omega\right)$. Thus, if we prove Stokes for $\rho_{i} \omega$, i.e., for forms that are compactly supported in a chart (interior or boundary), then we are done. (why?)
- So assume wlog that $\omega$ is compactly supported in a chart $(U, \phi)$. Wlog, $\phi$ is positively oriented (why?) Thus $\int_{M} d \omega=\int_{\phi(U)} d\left(\phi^{-1}\right)^{*} \omega$. Therefore, it is enough to assume that
- Cover the support of $\omega$ by finitely many charts (interior or boundary) $U_{i}$. Let $\rho_{i}$ be a partition-of-unity subordinate to this cover. Then $\int_{M} d \omega=\sum_{i} \int_{M} d\left(\rho_{i} \omega\right)$. Thus, if we prove Stokes for $\rho_{i} \omega$, i.e., for forms that are compactly supported in a chart (interior or boundary), then we are done. (why?)
- So assume wlog that $\omega$ is compactly supported in a chart $(U, \phi)$. Wlog, $\phi$ is positively oriented (why?) Thus $\int_{M} d \omega=\int_{\phi(U)} d\left(\phi^{-1}\right)^{*} \omega$. Therefore, it is enough to assume that $M$ is $\mathbb{H}^{n}$ or $\mathbb{R}^{n}$.
- Cover the support of $\omega$ by finitely many charts (interior or boundary) $U_{i}$. Let $\rho_{i}$ be a partition-of-unity subordinate to this cover. Then $\int_{M} d \omega=\sum_{i} \int_{M} d\left(\rho_{i} \omega\right)$. Thus, if we prove Stokes for $\rho_{i} \omega$, i.e., for forms that are compactly supported in a chart (interior or boundary), then we are done. (why?)
- So assume wlog that $\omega$ is compactly supported in a chart $(U, \phi)$. Wlog, $\phi$ is positively oriented (why?) Thus $\int_{M} d \omega=\int_{\phi(U)} d\left(\phi^{-1}\right)^{*} \omega$. Therefore, it is enough to assume that $M$ is $\mathbb{H}^{n}$ or $\mathbb{R}^{n}$.
- We have two cases.


## Proof of Stokes' theorem

## Proof of Stokes' theorem

- $M=\mathbb{R}^{n}$ :


## Proof of Stokes' theorem

- $M=\mathbb{R}^{n}$ : Let $\omega=\omega_{i} d x^{1} \ldots d x^{i-1} \wedge d \hat{x}^{i} \wedge \ldots$


## Proof of Stokes' theorem

- $M=\mathbb{R}^{n}$ : Let $\omega=\omega_{i} d x^{1} \ldots d x^{i-1} \wedge d \hat{x}^{i} \wedge \ldots$. Now

$$
\int_{\mathbb{R}^{n}} d \omega=\int_{\mathbb{R}^{n}} \sum_{i} \frac{\partial \omega_{i}}{\partial x^{i}}(-1)^{i-1} d x^{1} \wedge \ldots
$$

## Proof of Stokes' theorem

- $M=\mathbb{R}^{n}$ : Let $\omega=\omega_{i} d x^{1} \ldots d x^{i-1} \wedge d \hat{x^{i}} \wedge \ldots$. Now
$\int_{\mathbb{R}^{n}} d \omega=\int_{\mathbb{R}^{n}} \sum_{i} \frac{\partial \omega_{i}}{\partial x^{i}}(-1)^{i-1} d x^{1} \wedge \ldots$ This latter expression is 0 . (Why?)
- $M=\mathbb{R}^{n}$ : Let $\omega=\omega_{i} d x^{1} \ldots d x^{i-1} \wedge d \hat{x^{i}} \wedge \ldots$. Now
$\int_{\mathbb{R}^{n}} d \omega=\int_{\mathbb{R}^{n}} \sum_{i} \frac{\partial \omega_{i}}{\partial x^{i}}(-1)^{i-1} d x^{1} \wedge \ldots$ This latter expression is 0 . (Why?)
- $M=\mathbb{H}^{n}$ :
- $M=\mathbb{R}^{n}$ : Let $\omega=\omega_{i} d x^{1} \ldots d x^{i-1} \wedge d \hat{x^{i}} \wedge \ldots$. Now $\int_{\mathbb{R}^{n}} d \omega=\int_{\mathbb{R}^{n}} \sum_{i} \frac{\partial \omega_{i}}{\partial x^{i}}(-1)^{i-1} d x^{1} \wedge \ldots$ This latter expression is 0 . (Why?)
- $M=\mathbb{H}^{n}$ : Assume that the support is in
- $M=\mathbb{R}^{n}$ : Let $\omega=\omega_{i} d x^{1} \ldots d x^{i-1} \wedge d \hat{x^{i}} \wedge \ldots$. Now $\int_{\mathbb{R}^{n}} d \omega=\int_{\mathbb{R}^{n}} \sum_{i} \frac{\partial \omega_{i}}{\partial x^{i}}(-1)^{i-1} d x^{1} \wedge \ldots$ This latter expression is 0 . (Why?)
- $M=\mathbb{H}^{n}$ : Assume that the support is in $[-A, A]^{n-1} \times[0, A]$.
- $M=\mathbb{R}^{n}$ : Let $\omega=\omega_{i} d x^{1} \ldots d x^{i-1} \wedge d \hat{x^{i}} \wedge \ldots$. Now $\int_{\mathbb{R}^{n}} d \omega=\int_{\mathbb{R}^{n}} \sum_{i} \frac{\partial \omega_{i}}{\partial x^{i}}(-1)^{i-1} d x^{1} \wedge \ldots$ This latter expression is 0 . (Why?)
- $M=\mathbb{H}^{n}$ : Assume that the support is in $[-A, A]^{n-1} \times[0, A]$.

Now $\int_{\mathbb{H}^{n}} d \omega=\int_{-A}^{A} \ldots \int_{-A}^{A} \int_{0}^{A} \sum_{i} \frac{\partial \omega_{i}}{\partial x^{i}}(-1)^{i-1} d x^{n} \ldots=$ $\int_{\mathbb{R}^{n-1}}(-1)^{n} \omega_{n}(x, 0)+0$ (why?)

- $M=\mathbb{R}^{n}$ : Let $\omega=\omega_{i} d x^{1} \ldots d x^{i-1} \wedge d \hat{x^{i}} \wedge \ldots$. Now $\int_{\mathbb{R}^{n}} d \omega=\int_{\mathbb{R}^{n}} \sum_{i} \frac{\partial \omega_{i}}{\partial x^{( }}(-1)^{i-1} d x^{1} \wedge \ldots$ This latter expression is 0 . (Why?)
- $M=\mathbb{H}^{n}$ : Assume that the support is in $[-A, A]^{n-1} \times[0, A]$.

Now $\int_{\mathbb{H}^{n}} d \omega=\int_{-A}^{A} \ldots \int_{-A}^{A} \int_{0}^{A} \sum_{i} \frac{\partial \omega_{i}}{\partial x^{i}}(-1)^{i-1} d x^{n} \ldots=$ $\int_{\mathbb{R}^{n-1}}(-1)^{n} \omega_{n}(x, 0)+0$ (why?) Now the boundary $\mathbb{R}^{n-1}$ has orientation form

- $M=\mathbb{R}^{n}$ : Let $\omega=\omega_{i} d x^{1} \ldots d x^{i-1} \wedge d \hat{x^{i}} \wedge \ldots$ Now $\int_{\mathbb{R}^{n}} d \omega=\int_{\mathbb{R}^{n}} \sum_{i} \frac{\partial \omega_{i}}{\partial x^{i}}(-1)^{i-1} d x^{1} \wedge \ldots$ This latter expression is 0 . (Why?)
- $M=\mathbb{H}^{n}$ : Assume that the support is in $[-A, A]^{n-1} \times[0, A]$.

Now $\int_{\mathbb{H}^{n}} d \omega=\int_{-A}^{A} \ldots \int_{-A}^{A} \int_{0}^{A} \sum_{i} \frac{\partial \omega_{i}}{\partial x^{i}}(-1)^{i-1} d x^{n} \ldots=$ $\int_{\mathbb{R}^{n-1}}(-1)^{n} \omega_{n}(x, 0)+0$ (why?) Now the boundary $\mathbb{R}^{n-1}$ has orientation form $d x^{1} \wedge d x^{2} \ldots\left(-\frac{\partial}{\partial x^{n}}, \ldots\right)=(-1)^{n} d x^{1} \wedge \ldots$.

- $M=\mathbb{R}^{n}$ : Let $\omega=\omega_{i} d x^{1} \ldots d x^{i-1} \wedge d \hat{x^{i}} \wedge \ldots$ Now $\int_{\mathbb{R}^{n}} d \omega=\int_{\mathbb{R}^{n}} \sum_{i} \frac{\partial \omega_{i}}{\partial x^{i}}(-1)^{i-1} d x^{1} \wedge \ldots$ This latter expression is 0 . (Why?)
- $M=\mathbb{H}^{n}$ : Assume that the support is in $[-A, A]^{n-1} \times[0, A]$.

Now $\int_{\mathbb{H}^{n}} d \omega=\int_{-A}^{A} \ldots \int_{-A}^{A} \int_{0}^{A} \sum_{i} \frac{\partial \omega_{i}}{\partial x^{i}}(-1)^{i-1} d x^{n} \ldots=$ $\int_{\mathbb{R}^{n-1}}(-1)^{n} \omega_{n}(x, 0)+0$ (why?) Now the boundary $\mathbb{R}^{n-1}$ has orientation form $d x^{1} \wedge d x^{2} \ldots\left(-\frac{\partial}{\partial x^{n}}, \ldots\right)=(-1)^{n} d x^{1} \wedge \ldots$. Thus the last integral equals

- $M=\mathbb{R}^{n}$ : Let $\omega=\omega_{i} d x^{1} \ldots d x^{i-1} \wedge d \hat{x^{i}} \wedge \ldots$ Now $\int_{\mathbb{R}^{n}} d \omega=\int_{\mathbb{R}^{n}} \sum_{i} \frac{\partial \omega_{i}}{\partial x^{i}}(-1)^{i-1} d x^{1} \wedge \ldots$ This latter expression is 0 . (Why?)
- $M=\mathbb{H}^{n}$ : Assume that the support is in $[-A, A]^{n-1} \times[0, A]$. Now $\int_{\mathbb{H}^{n}} d \omega=\int_{-A}^{A} \ldots \int_{-A}^{A} \int_{0}^{A} \sum_{i} \frac{\partial \omega_{i}}{\partial x^{i}}(-1)^{i-1} d x^{n} \ldots=$ $\int_{\mathbb{R}^{n-1}}(-1)^{n} \omega_{n}(x, 0)+0$ (why?) Now the boundary $\mathbb{R}^{n-1}$ has orientation form $d x^{1} \wedge d x^{2} \ldots\left(-\frac{\partial}{\partial x^{n}}, \ldots\right)=(-1)^{n} d x^{1} \wedge \ldots$. Thus the last integral equals $\int_{\partial \mathbb{H}^{n}} \omega$.


## Consequences of Stokes

## Consequences of Stokes

- All the classical theorems (


## Consequences of Stokes

- All the classical theorems (Divergence, Stokes, Green)


## Consequences of Stokes

- All the classical theorems (Divergence, Stokes, Green) are special cases.


## Consequences of Stokes

- All the classical theorems (Divergence, Stokes, Green) are special cases.
- If $S$ is a compact oriented submanifold


## Consequences of Stokes

- All the classical theorems (Divergence, Stokes, Green) are special cases.
- If $S$ is a compact oriented submanifold of a smooth manifold $M$,


## Consequences of Stokes

- All the classical theorems (Divergence, Stokes, Green) are special cases.
- If $S$ is a compact oriented submanifold of a smooth manifold $M$, and $\omega$ is a closed $k$-form on $M$, such that


## Consequences of Stokes

- All the classical theorems (Divergence, Stokes, Green) are special cases.
- If $S$ is a compact oriented submanifold of a smooth manifold $M$, and $\omega$ is a closed $k$-form on $M$, such that $\int_{S} \omega \neq 0$,


## Consequences of Stokes

- All the classical theorems (Divergence, Stokes, Green) are special cases.
- If $S$ is a compact oriented submanifold of a smooth manifold $M$, and $\omega$ is a closed $k$-form on $M$, such that $\int_{S} \omega \neq 0$, then $\omega$ is NOT exact,


## Consequences of Stokes

- All the classical theorems (Divergence, Stokes, Green) are special cases.
- If $S$ is a compact oriented submanifold of a smooth manifold $M$, and $\omega$ is a closed $k$-form on $M$, such that $\int_{S} \omega \neq 0$, then $\omega$ is NOT exact, and $S$ is NOT the boundary of a submanifold (why?)


## Consequences of Stokes

- All the classical theorems (Divergence, Stokes, Green) are special cases.
- If $S$ is a compact oriented submanifold of a smooth manifold $M$, and $\omega$ is a closed $k$-form on $M$, such that $\int_{S} \omega \neq 0$, then $\omega$ is NOT exact, and $S$ is NOT the boundary of a submanifold (why?)
- Thus, $\omega=\frac{x d y-y d x}{x^{2}+y^{2}}$ is closed but not exact.


## Consequences of Stokes

- All the classical theorems (Divergence, Stokes, Green) are special cases.
- If $S$ is a compact oriented submanifold of a smooth manifold $M$, and $\omega$ is a closed $k$-form on $M$, such that $\int_{S} \omega \neq 0$, then $\omega$ is NOT exact, and $S$ is NOT the boundary of a submanifold (why?)
- Thus, $\omega=\frac{x d y-y d x}{x^{2}+y^{2}}$ is closed but not exact.
- Suppose $M$ is an oriented compact smooth manifold with boundary.


## Consequences of Stokes

- All the classical theorems (Divergence, Stokes, Green) are special cases.
- If $S$ is a compact oriented submanifold of a smooth manifold $M$, and $\omega$ is a closed $k$-form on $M$, such that $\int_{S} \omega \neq 0$, then $\omega$ is NOT exact, and $S$ is NOT the boundary of a submanifold (why?)
- Thus, $\omega=\frac{x d y-y d x}{x^{2}+y^{2}}$ is closed but not exact.
- Suppose $M$ is an oriented compact smooth manifold with boundary. There is no smooth retraction of $M$ onto its boundary:


## Consequences of Stokes

- All the classical theorems (Divergence, Stokes, Green) are special cases.
- If $S$ is a compact oriented submanifold of a smooth manifold $M$, and $\omega$ is a closed $k$-form on $M$, such that $\int_{S} \omega \neq 0$, then $\omega$ is NOT exact, and $S$ is NOT the boundary of a submanifold (why?)
- Thus, $\omega=\frac{x d y-y d x}{x^{2}+y^{2}}$ is closed but not exact.
- Suppose $M$ is an oriented compact smooth manifold with boundary. There is no smooth retraction of $M$ onto its boundary: Recall that $r: M \rightarrow \partial M$ is a retract if


## Consequences of Stokes

- All the classical theorems (Divergence, Stokes, Green) are special cases.
- If $S$ is a compact oriented submanifold of a smooth manifold $M$, and $\omega$ is a closed $k$-form on $M$, such that $\int_{S} \omega \neq 0$, then $\omega$ is NOT exact, and $S$ is NOT the boundary of a submanifold (why?)
- Thus, $\omega=\frac{x d y-y d x}{x^{2}+y^{2}}$ is closed but not exact.
- Suppose $M$ is an oriented compact smooth manifold with boundary. There is no smooth retraction of $M$ onto its boundary: Recall that $r: M \rightarrow \partial M$ is a retract if $r$ is identity on $\partial M$.


## Consequences of Stokes

- All the classical theorems (Divergence, Stokes, Green) are special cases.
- If $S$ is a compact oriented submanifold of a smooth manifold $M$, and $\omega$ is a closed $k$-form on $M$, such that $\int_{S} \omega \neq 0$, then $\omega$ is NOT exact, and $S$ is NOT the boundary of a submanifold (why?)
- Thus, $\omega=\frac{x d y-y d x}{x^{2}+y^{2}}$ is closed but not exact.
- Suppose $M$ is an oriented compact smooth manifold with boundary. There is no smooth retraction of $M$ onto its boundary: Recall that $r: M \rightarrow \partial M$ is a retract if $r$ is identity on $\partial M$. If there is a retract,


## Consequences of Stokes

- All the classical theorems (Divergence, Stokes, Green) are special cases.
- If $S$ is a compact oriented submanifold of a smooth manifold $M$, and $\omega$ is a closed $k$-form on $M$, such that $\int_{S} \omega \neq 0$, then $\omega$ is NOT exact, and $S$ is NOT the boundary of a submanifold (why?)
- Thus, $\omega=\frac{x d y-y d x}{x^{2}+y^{2}}$ is closed but not exact.
- Suppose $M$ is an oriented compact smooth manifold with boundary. There is no smooth retraction of $M$ onto its boundary: Recall that $r: M \rightarrow \partial M$ is a retract if $r$ is identity on $\partial M$. If there is a retract, then suppose $\omega$ is an orientation form on $\partial M$.


## Consequences of Stokes

- All the classical theorems (Divergence, Stokes, Green) are special cases.
- If $S$ is a compact oriented submanifold of a smooth manifold $M$, and $\omega$ is a closed $k$-form on $M$, such that $\int_{S} \omega \neq 0$, then $\omega$ is NOT exact, and $S$ is NOT the boundary of a submanifold (why?)
- Thus, $\omega=\frac{x d y-y d x}{x^{2}+y^{2}}$ is closed but not exact.
- Suppose $M$ is an oriented compact smooth manifold with boundary. There is no smooth retraction of $M$ onto its boundary: Recall that $r: M \rightarrow \partial M$ is a retract if $r$ is identity on $\partial M$. If there is a retract, then suppose $\omega$ is an orientation form on $\partial M$. Then $r^{*} \omega$ is a smooth $n-1$ form on $M$


## Consequences of Stokes

- All the classical theorems (Divergence, Stokes, Green) are special cases.
- If $S$ is a compact oriented submanifold of a smooth manifold $M$, and $\omega$ is a closed $k$-form on $M$, such that $\int_{S} \omega \neq 0$, then $\omega$ is NOT exact, and $S$ is NOT the boundary of a submanifold (why?)
- Thus, $\omega=\frac{x d y-y d x}{x^{2}+y^{2}}$ is closed but not exact.
- Suppose $M$ is an oriented compact smooth manifold with boundary. There is no smooth retraction of $M$ onto its boundary: Recall that $r: M \rightarrow \partial M$ is a retract if $r$ is identity on $\partial M$. If there is a retract, then suppose $\omega$ is an orientation form on $\partial M$. Then $r^{*} \omega$ is a smooth $n-1$ form on $M$ that restricts to $\omega$ on $\partial M$.


## Consequences of Stokes

- All the classical theorems (Divergence, Stokes, Green) are special cases.
- If $S$ is a compact oriented submanifold of a smooth manifold $M$, and $\omega$ is a closed $k$-form on $M$, such that $\int_{S} \omega \neq 0$, then $\omega$ is NOT exact, and $S$ is NOT the boundary of a submanifold (why?)
- Thus, $\omega=\frac{x d y-y d x}{x^{2}+y^{2}}$ is closed but not exact.
- Suppose $M$ is an oriented compact smooth manifold with boundary. There is no smooth retraction of $M$ onto its boundary: Recall that $r: M \rightarrow \partial M$ is a retract if $r$ is identity on $\partial M$. If there is a retract, then suppose $\omega$ is an orientation form on $\partial M$. Then $r^{*} \omega$ is a smooth $n-1$ form on $M$ that restricts to $\omega$ on $\partial M$. Now $\int_{M} d r^{*} \omega=\int_{\partial M} \omega>0$.


## Consequences of Stokes

- All the classical theorems (Divergence, Stokes, Green) are special cases.
- If $S$ is a compact oriented submanifold of a smooth manifold $M$, and $\omega$ is a closed $k$-form on $M$, such that $\int_{S} \omega \neq 0$, then $\omega$ is NOT exact, and $S$ is NOT the boundary of a submanifold (why?)
- Thus, $\omega=\frac{x d y-y d x}{x^{2}+y^{2}}$ is closed but not exact.
- Suppose $M$ is an oriented compact smooth manifold with boundary. There is no smooth retraction of $M$ onto its boundary: Recall that $r: M \rightarrow \partial M$ is a retract if $r$ is identity on $\partial M$. If there is a retract, then suppose $\omega$ is an orientation form on $\partial M$. Then $r^{*} \omega$ is a smooth $n-1$ form on $M$ that restricts to $\omega$ on $\partial M$. Now $\int_{M} d r^{*} \omega=\int_{\partial M} \omega>0$. However, $d\left(r^{*} \omega\right)=r^{*}(d \omega)=0$ !


## Looking beyond

## Looking beyond

- Differential topology (


## Looking beyond

- Differential topology (When are two manifolds homeomorphic but not diffeomorphic?)


## Looking beyond

- Differential topology (When are two manifolds homeomorphic but not diffeomorphic?)
- Riemannian geometry (


## Looking beyond

- Differential topology (When are two manifolds homeomorphic but not diffeomorphic?)
- Riemannian geometry (distances, angles, curvature, congruence/isomorphism, finding the best metric, etc)


## Looking beyond

- Differential topology (When are two manifolds homeomorphic but not diffeomorphic?)
- Riemannian geometry (distances, angles, curvature, congruence/isomorphism, finding the best metric, etc)
- Geometric analysis (


## Looking beyond

- Differential topology (When are two manifolds homeomorphic but not diffeomorphic?)
- Riemannian geometry (distances, angles, curvature, congruence/isomorphism, finding the best metric, etc)
- Geometric analysis (PDE on manifolds)


## Looking beyond

- Differential topology (When are two manifolds homeomorphic but not diffeomorphic?)
- Riemannian geometry (distances, angles, curvature, congruence/isomorphism, finding the best metric, etc)
- Geometric analysis (PDE on manifolds)
- Symplectic geometry (


## Looking beyond

- Differential topology (When are two manifolds homeomorphic but not diffeomorphic?)
- Riemannian geometry (distances, angles, curvature, congruence/isomorphism, finding the best metric, etc)
- Geometric analysis (PDE on manifolds)
- Symplectic geometry (Classical mechanics on manifolds)


## Looking beyond

- Differential topology (When are two manifolds homeomorphic but not diffeomorphic?)
- Riemannian geometry (distances, angles, curvature, congruence/isomorphism, finding the best metric, etc)
- Geometric analysis (PDE on manifolds)
- Symplectic geometry (Classical mechanics on manifolds)
- Algebraic geometry (


## Looking beyond

- Differential topology (When are two manifolds homeomorphic but not diffeomorphic?)
- Riemannian geometry (distances, angles, curvature, congruence/isomorphism, finding the best metric, etc)
- Geometric analysis (PDE on manifolds)
- Symplectic geometry (Classical mechanics on manifolds)
- Algebraic geometry (Zeroes of polynomials)


## Looking beyond

- Differential topology (When are two manifolds homeomorphic but not diffeomorphic?)
- Riemannian geometry (distances, angles, curvature, congruence/isomorphism, finding the best metric, etc)
- Geometric analysis (PDE on manifolds)
- Symplectic geometry (Classical mechanics on manifolds)
- Algebraic geometry (Zeroes of polynomials)
- Arithmetic geometry and number theory (


## Looking beyond

- Differential topology (When are two manifolds homeomorphic but not diffeomorphic?)
- Riemannian geometry (distances, angles, curvature, congruence/isomorphism, finding the best metric, etc)
- Geometric analysis (PDE on manifolds)
- Symplectic geometry (Classical mechanics on manifolds)
- Algebraic geometry (Zeroes of polynomials)
- Arithmetic geometry and number theory (Modular forms and elliptic curves for instance)


## Looking beyond

- Differential topology (When are two manifolds homeomorphic but not diffeomorphic?)
- Riemannian geometry (distances, angles, curvature, congruence/isomorphism, finding the best metric, etc)
- Geometric analysis (PDE on manifolds)
- Symplectic geometry (Classical mechanics on manifolds)
- Algebraic geometry (Zeroes of polynomials)
- Arithmetic geometry and number theory (Modular forms and elliptic curves for instance)
- Applications (


## Looking beyond

- Differential topology (When are two manifolds homeomorphic but not diffeomorphic?)
- Riemannian geometry (distances, angles, curvature, congruence/isomorphism, finding the best metric, etc)
- Geometric analysis (PDE on manifolds)
- Symplectic geometry (Classical mechanics on manifolds)
- Algebraic geometry (Zeroes of polynomials)
- Arithmetic geometry and number theory (Modular forms and elliptic curves for instance)
- Applications (Protein folding,


## Looking beyond

- Differential topology (When are two manifolds homeomorphic but not diffeomorphic?)
- Riemannian geometry (distances, angles, curvature, congruence/isomorphism, finding the best metric, etc)
- Geometric analysis (PDE on manifolds)
- Symplectic geometry (Classical mechanics on manifolds)
- Algebraic geometry (Zeroes of polynomials)
- Arithmetic geometry and number theory (Modular forms and elliptic curves for instance)
- Applications (Protein folding, control theory,


## Looking beyond

- Differential topology (When are two manifolds homeomorphic but not diffeomorphic?)
- Riemannian geometry (distances, angles, curvature, congruence/isomorphism, finding the best metric, etc)
- Geometric analysis (PDE on manifolds)
- Symplectic geometry (Classical mechanics on manifolds)
- Algebraic geometry (Zeroes of polynomials)
- Arithmetic geometry and number theory (Modular forms and elliptic curves for instance)
- Applications (Protein folding, control theory, general relativity,


## Looking beyond

- Differential topology (When are two manifolds homeomorphic but not diffeomorphic?)
- Riemannian geometry (distances, angles, curvature, congruence/isomorphism, finding the best metric, etc)
- Geometric analysis (PDE on manifolds)
- Symplectic geometry (Classical mechanics on manifolds)
- Algebraic geometry (Zeroes of polynomials)
- Arithmetic geometry and number theory (Modular forms and elliptic curves for instance)
- Applications (Protein folding, control theory, general relativity, string theory,


## Looking beyond

- Differential topology (When are two manifolds homeomorphic but not diffeomorphic?)
- Riemannian geometry (distances, angles, curvature, congruence/isomorphism, finding the best metric, etc)
- Geometric analysis (PDE on manifolds)
- Symplectic geometry (Classical mechanics on manifolds)
- Algebraic geometry (Zeroes of polynomials)
- Arithmetic geometry and number theory (Modular forms and elliptic curves for instance)
- Applications (Protein folding, control theory, general relativity, string theory, statistical mechanics, etc)

